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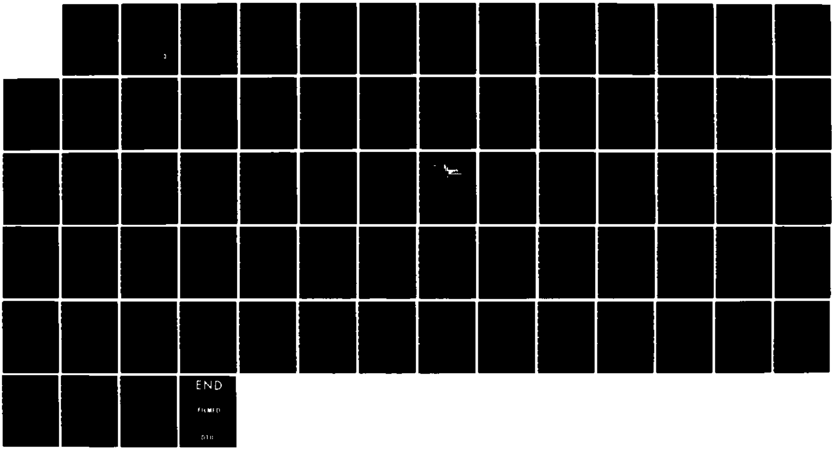

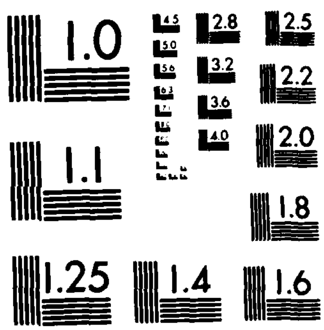


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# STABILITY OF EMBANKMENTS

# ON SOFT CLAY

Final Technical Report

Part 1 of 3: Tests with centrifuge vane and

penetrometers on clay cakes in a normal gravity field

by

M S S Almeida and R H G Parry

November 1984

United States Army

EUROPEAN RESEARCH OFFICE OF THE U S ARMY

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Small vane and penetrometer devices have been developed to measured soil properties in centrifuge models during flight. Early models of these devices, and subsequent improved devices which allow separation of shaft friction from cone or vane resistance, are described, and results presented from tests on consolidated clay cakes in a normal gravity field. A small piezocone has also been developed. Vane results are shown to be strongly influenced by vane diameter, but not vane height, by elapsed time between insertion and rotation

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of the vane and by the rate of rotation. From these results a vane size of 18 mm diameter by 14 mm high is recommended with a rotation rate of 72°/min. A penetration rate of 5 mm/s is found to be suitable for a 10 mm diameter cone although in fact penetration rate was found to have little influence on the measured cone resistance. A consistent relationship could not be established between cone resistance and vane strength. The ratio of cone resistance to vane strength was found to increase with increasing over-consolidation ratio, but was also found to depend on various other factors such as vane and cone sizes and testing rates. The values also differed considerably between the two clays used, Gault clay and kaolin. Thus, while the penetrometer is a simple test to use in the centrifuge and has the advantage of giving a continuous profile of resistance with depth, some care is required in converting the cone resistance into undrained shear strength. Tests with the small piezocone show that the ratio of pore pressure to point resistance decreases slightly with increasing overconsolidation ratio, but not enough for this ratio to be used as a method for determining OCR. Dissipation tests with the piezocone yield values of coefficient of consolidation agreeing very well with those from swelling tests on the clay cakes.

CONTENTS

## 1. Introduction

It is usually more convenient to use reconstituted or laboratory prepared soil rather than undisturbed soil for centrifuge model tests (Schofield 1980). In choosing a suitable soil a number of factors must be considered, not the least of which is permeability. Centrifuge time is expensive and highly impermeable soils can take a long time to consolidate. Using a cake size which in Cambridge models is typically 180 mm thick (Bassett, Davies, Gunn and Parry 1981), kaolin, which is a very permeable clay ($k = 2.5 \times 10^{-9}$ m/s), takes 8 to 12 hours to achieve effectively complete consolidation from one stress state to a new stress state. Less permeable clays would require consolidation times much greater than this, which is impracticable. Thus, at Cambridge kaolin is usually used provided it is compatible with the requirements of the model.

As a result of using a relatively permeable clay, two problems arise when the centrifuge is stopped during a test, or after a test has been conducted:

1. As the clay is fairly permeable the voids are too large to sustain high pore water tensions and air entry or cavitation can occur.
2. The high permeability allows any excess water on the soil surface, in sand layers or in drainage stones and ducts to be drawn into the clay by the negative pore pressure.

Both of these phenomena have the effect of softening the clay and reducing the shear strength, and consequently any strength or deformation parameters measured after the centrifuge is stopped may be very different from the relevant values while the centrifuge is in flight. Fig.1.1 shows undrained shear strengths measured in a kaolin clay bed during flight and after stopping the centrifuge (Davies 1981). A stress history was induced into the 180 mm deep bed of clay so that, at 100g, the overconsolidation ratio decreased from 6.5 at the clay surface to 1.0 at, and below mid-height. It can be seen that a 50% to 60% drop in strength occurs on stopping the centrifuge.

In order to measure undrained shear strengths during flight a vane apparatus was developed by Davies (1981) which could be attached to the centrifuge model package. This is referred to as the Mark I vane in this report. Using this apparatus Cheah (1981) performed tests on the

laboratory floor to investigate a number of aspects of vane testing in clays, including the influence of vane rotation rate and vane geometry. The vane apparatus and results of tests by Cheah are given in Section 2. Further tests by Almeida (unpublished) are described in Section 3. By modifying the vane equipment Cheah devised a cone penetrometer, Mark I. Using this equipment he studied the influence of penetration rate and was also able to compare cone resistance with undrained strengths. This work has also been further extended by Almeida, as described in Section 3.

A number of problems were found to exist with the early vane and penetrometer equipment. These included significant shaft frictions which were not being separated from the measurements by the vane and cone, uncertainty about vane rotation rates and the drawback that the apparatus could not be moved during flight to measure strength profiles at different locations in the package. Modifications to the vane and cone devices were developed by Almeida to enable vane or tip resistance to be separated from shaft friction. A further modification was the development of a piezocone. These equipments are described in Sections 4 and 5. This report is restricted to tests performed in the laboratory in the natural gravity field. A new apparatus developed to perform tests 'in flight' at different positions in the centrifuge package, is described elsewhere (Almeida and Parry, 1983).

## 2. Tests by Cheah using Mark 1 Vane devices

### 2.1 Vane Apparatus Mark 1

In designing the vane it was essential that it should be compact, as space is restricted on the centrifuge package, and should be able to sustain accelerations up to at least 100g. As seen in fig.2.1 and fig.2.2 the apparatus (Davies, 1981, Davies and Parry, 1982) consists of four major elements:

1. Vane blades A, driving shaft B, bearing C and torque motor D
2. Moving platform E
3. Motor F, gearing mechanism G and threaded rod H to drive the moving platform E vertically, which advances or retracts the vane.
4. A frame J which attaches to the centrifuge package. In

fig.2.1 and fig.2.2 it is shown fixed to an extension of the base plate K which supports a sand bearing hopper, used to construct embankments during flight.

Vane blades A are machined from a solid piece of stainless steel. A 19 mm dia. by 28 mm deep vane was used by Davies (1981) and Cheah (1981). These dimensions correspond to a commercially available laboratory vane which has in the past been used extensively in Cambridge for measuring shear strengths in centrifuge models after stopping the centrifuge. The vane shaft B is made up from 6.34 mm outside diameter, 18 gauge dural tubing, with a 10 mm length near the top having a thinner wall with bonded strain gauges M to measure torque. Before testing, the shaft is coated with a teflon layer and lubricated with silicone grease. A 6 volt reversible DC motor D, which connects to the vane shaft through bearing C, rotates the vane at 86$^{\circ}$ per min. This is more rapid than the 12$^{\circ}$ per minute recommended by BS 1377, but this slower rate with a small vane in a permeable clay would introduce the possibility of some drainage around the vane during the test. This point is further discussed later.

The moving platform E is triangular in plan and constrained to move vertically by three vertical rods, comprising part of the frame J. Vertical motion is imparted to the platform by the 15v DC motor F acting through a simple gearing system and screw drive G such that one revolution of the motor raises or lowers the threaded rod H, and hence the moving platform and vane, by 1 mm. As the motor speed is 42 rpm, the rate of vertical drive of the vane is 10 mm/min. A DC potentiometer displacement transducer L fixed to the top of the frame monitors the vertical progress of the moving platform, and hence the penetration of the vane. The vane can be moved a maximum vertical distance of 200 mm. The vane is operated by electrical signals through the slip rings on the centrifuge and signals are received from the strain gauges measuring torque and from the vertical displacement transducer. The angular rotation at anytime can be obtained from the measured time of rotation and the known speed of the torque motor.

After completion of each test, motor D is reversed to return the vane to its original position, and the vane then advanced to the next test depth. After completion of all tests the vane is retracted from the soil.

The vane output is usually recorded manually and also on magnetic tape, which can be used to produce an x-y plot. A typical plot is shown in

fig.2.3. The undrained strength is taken from the peak reading, which is reached about 20 seconds after the start of the test.

## 2.2 Influence of vane geometry and rotation rate

Flaate(1966) and Lacasse et al(1978) amongst others have summarized the factors influencing the results of vane tests. The main factors are: geometry of the vane blades, rate of rotation, disturbance during vane insertion, delay between vane insertion and rotation and friction along the shaft. Cheah(1981) used the vane described above to inspect the influence of vane geometry and rate of rotation in reconsolidated specimens of kaolin. Four rectangular blades with an area ratio of 14% and dimensions presented in Table 1 were used in his studies.

Cheah consolidated kaolin samples from a slurry using either a rectangular consolidometer 740 mm long, 150 mm wide and a 460 mm sample depth or a round consolidometer 850 mm high and 370 mm deep. Samples were prepared under three different stress conditions:

(1) Samples normally consolidated under 150 kPa and tests performed with this pressure mantained. This was achieved by having removable plugs in the consolidometer piston, through which the tests could be performed.

(2) Samples consolidated under 150 kPa, then allowed to swell to 50 kPa and tests performed with this pressure mantained.

(3) As (2), but with the pressure removed to zero. Some limited swelling probably occurred during removal of pressure from 50 kPa to zero presure.

At the same rotation rate of $86^{o}$/min these studies showed a 30% decrease of undrained shear strength with increase from 18 mm to 36 mm in the diameter of the vane blades, as shown in fig.2.4 for tests under zero pressure. On the other hand the results from vane blades A and B indicating that the vane height had very little influence on measured undrained strength. Davies(1981) used vane blade A in site investigations during centrifuge tests. However due to the small thickness of the clay cakes(180 mm), the 25 mm height vane blades limited the number of tests in depth and also gave the possibility of large changes in shear strength over the height of the vane itself.

Recent centrifuge tests performed by Almeida using even shallower clay cakes(160 mm) have increased the need for vane blades of small height. Hence vane B which produced similar shear strengths to vane A has now been adopted for laboratory and centrifuge tests.

Cheah(1981) also studied the influence of the rate of rotation, varying it between $4^{o}$/min and $6480^{o}$/min. Typical results are shown in fig. 2.5. The lowest values of $c_u$ were measured at a rotation rate of $40^{o}$/min. At slower rates the strengths were increased by drainage of the excess of pore presure around the vane. The increase of $c_u$ with the rate of rotation for the faster tests is a strain rate effect on the undrained shear strength which is only 2.5% per log cycle.

Quantitative figures given by the apparatus shown in fig. 2.1 have to be analyzed with caution because of the amount of friction developed in the vane shaft during rotation, even when coated with silicone grease. This will be shown later. Moreover the angular rotation was not directly measured, but estimated by the combination of the measured time of rotation and the nominal speed of the motor under no load. These motors slow down when loaded which makes those estimates unreliable.

### 2.3 Cone penetrometer Mark 1

Several factors influence the results of cone tests and they have been summarized recently(de Ruiter,1982). Some of the most important factors are rate of penetration, geometry and roughness of the cone tip.

Cheah(1981) modified the travelling part of the vane apparatus(fig.2.1) to incorporate a cone penetrometer. The penetrometer shown in fig.2.6 consists of a $60^{o}$ cone of 10mm diameter attached to a shaft. The diameter of the shaft was reduced to 8mm and covered with a layer of teflon to reduce shaft friction. It was hoped in this way to reduce shaft friction to a negligible amount. A load cell connected to the top of the cone measured the load during cone penetration. The rate of penetration could be altered by using different motors and by altering the voltage supply to the motors.

Cheah performed tests varying the rate of penetration between 0.23mm/sec and 5.6mm/sec. The highest point resistance was observed for the smallest rate of penetration as shown in fig.2.7. The smallest point resistance was achieved at about 1mm/sec, and it then increased gradually

for rates up to 5.6 mm/sec. As for vane tests the smallest rate of penetration allows some drainage and the increase of the point resistance from 1 mm/sec to 5.6 mm/sec is due to the strain rate effect.

Rates of penetration used in practice range from 10 mm/sec to 20 mm/sec, which are much higher than those used by Cheah and it was necessary to carry out further tests at higher rates of penetration, as described in section 3.

## 3. Tests by Almeida using Mark I devices.

A programme of cone and vane tests was planned to clarify some points unresolved from previous studies. It was decided to use for these preliminary tests the same cone and vane apparatuses described earlier, despite their limitations.

### 3.1 Experimental procedures

A slurry of Speswhite kaolin was prepared with an initial water content of 124.5%, following normal procedure used at Cambridge. The clay cake was consolidated to 150 kPa in the 850 mm diameter consolidometer shown in fig. 3.1. Twelve plugs on the top of the piston allowed cone and vane tests to be carried out under vertical pressure. During tests a special piston plug with the same dimension as the other 12 plugs but with a central tapped hole to guide cone and vane shafts was put at the required position in the piston.

The clay specimen was initially consolidated to 150 kPa and cone and vane tests were carried out at this pressure and also after swelling under 50 kPa and at zero vertical pressure. No water was allowed into the clay for swelling from 50 kPa to zero pressure.

A PDP-8/E computer interfaced with a teletype and a fast scan punch tape together with a BRYAN X-Y plotter and a signal amplifier were used for data acquisition. Torque against time(or angular rotation) for vane tests and point resistance against depth for penetrometer tests were plotted during the tests. Additionally, data punched onto tape or printed in the teletype were used as a check of the plotted curves. Hand readings were also taken from a DVM.

**3.2 Vane tests**

The influence of the following factors were investigated in the tests described here: a) two angular rates of rotation: $20^{o}$/min and $72^{o}$/min; b) three different time delays between vane insertion and test: 1, 6 and 20 minutes;

As drive motor speeds can vary under load the simple arrangement shown in fig.3.2 was used to estimate the angular rate of rotation. The angle of rotation could be computed by the movement of the chord around the pulley, causing displacement of the LVDT. Measured angles of rotation at peak torque are shown in fig.3.3. It is seen that angles of rotation for peak range between $6^{o}$ and $15^{o}$, which are much lower figures than previously estimated by Cheah(1981) and Davies(1981), as seen in fig.2.3. The measured rate of rotation was $72^{o}$/min which is lower than the rated motor speed $86^{o}$/min quoted by Cheah(1981) and Davies(1981). After some tests it was found that the arrangement for measuring the angle of rotation shown in fig.3.2 was affecting the measured torque, due to the spring acting in the opposite direction of the rotation. Those tests were then halted and a new method described in section 4 was devised.

Results of tests investigating the influence of the time between vane insertion and start of the test are shown in fig.3.4 for different applied pressures and rotation rates. For the higher rate of rotation the strength increase, as the time before test increases, which is almost certainly due to dissipation of excess of pore pressures set up during vane insertion. However the opposite trend was observed for tests at lower rate of rotation. The reason for this is not very clear.

For pratical reasons the time necessary between vane insertion and vane test is about 1 minute in laboratory and centrifuge tests and results shown here ilustrate that this time has to be kept constant to make results consistent.

The influence of the rate of rotation on values of $c_u$ is ilustrated in fig.3.5 for different applied pressures at time before test. Except for $\sigma$=0, t=1 min, higher strengths were observed at higher rate of rotation. Results obtained here show somewhat stronger influence of the rate of rotation than studies by Cheah(1980).

Perlow and Richards(1977) have recommended a standard angular velocity of 0.15 mm/sec for both field and laboratory vane tests to make results

comparable. Rates of rotation of 20°/min and 72°/min correspond to angular velocities of 0.05 mm/sec and 0.18 mm/ : and therefore the upper limit would be recommended. Blight(1978) discusses the recommendations of the above authors and suggests that angular velocities should not be standardised but depend on the type of soil. Blight(1968) has suggested that a time factor T taking into account the coefficient of consolidation $c_v$ and the vane diameter D should be the basis for the computation of the angular velocity. A practical criterion for the undrained condition(degree of drainage less than about 10%) was proposed by Blight(1968) as

$$T=c_v.t_f/D^2 < 0.02 \text{ to } 0.04 \tag{3.1}$$

in which $t_f$ is the time to failure. The time factor for tests in Speswhite kaolin for tests at 72°/min is about T=0.035 which is within the recommended range.

Based on experimental studies Matsui and Abe(1981) suggest that the undrained condition for a kaolin clay can be satisfied in cases of angular rotations greater than 60°/min. These recommendations are confirmed by coupled consolidation numerical analyses using a elastoplastic strain-hardening model similar to Cam-clay.

Therefore a rate of rotation equal to 72°/min appears satisfactory for tests of kaolin clays and has been adopted for the investigation of embankment stability on soft clays in the centrifuge. It has also been adopted for making comparative tests between vane strengths and cone penetrometer resistances.

The influence of OCR and vertical stresses on the undrained strength is illustrated in fig.3.6. The increase of strength with depth suggests that friction due to the shaft is influencing the measured values. A means suggested to overcome this is described in section 4.

### 3.3 Cone penetrometer tests

Using the cone penetrometer apparatus Mark I described in subsection 2.3, factors influencing the penetrometer resistance $q_c$, such as rate of penetration and overburden pressure, were observed.

Values of $q_c$ increased with the increase of the rate of penetration, as shown in fig. 3.7, for different applied pressures. The influence of vertical stresses on $q_c$ is illustrated in fig. 3.8. The low values of $q_c$ at

shallow depths, particularly noticeable at higher stresses, were due in part to a decrease in stresses in the zone immediately below the plugs, when piston plugs were exchanged for test plugs to allow access of the penetrometer. The increase of measured $q_c$ with depth below 60 mm is due to shaft friction. It is apparent from this that the shaft adhesion in the Mark I cone was contributing to the measured resistance and therefore the true point resistance was not being measured by the load cell at the top of the shaft.

Results of vane and penetrometer tests are usually correlated using the expressions,

$$N_c = \frac{q_c - \sigma}{c_u} \tag{3.2}$$

or

$$N_k = \frac{q_c}{c_u} \tag{3.3}$$

Computed values of $N_c$ using the above expression and cone resistance values in fig.3.8 are shown in fig.3.9 for different applied stresses and different rates of penetration. The vane rate of rotation was $72^{\circ}$/min. Values of $N_c$ increase with rate of penetration and OCR. However these $N_c$ values should be treated with caution as shaft friction was contributing to both cone and vane resistances.

### 3.4 Conclusions from the preliminary tests

It may be concluded from these tests employing the Mark I equipment that:

(a) it is important to measure directly the angular vane rotation during tests, and not rely on rated motor speeds to obtain the true torque-angular rotation curve;

(b) a rate of insertion of 0.25 mm/s for the vane seems to be suitable and the time allowed to elapse before rotating the

blade should be kept to a minimum;

(c) a rotation of 72°/min should be adopted for vane tests in kaolin;

(d) torque due to blade shear and torque due to shaft friction should be separated in order to allow proper computation of the shear strength;

(e) resistances measured during cone penetration increase with the rate of penetration;

(f) even with a reduced shaft diameter and teflon coating, the amount of shaft friction is significant, hence separate measurements should be made of point and shaft resistances;

(g) removal of piston plugs to allow access for the vane and penetrometer causes stress relief close to the clay surface and thus the smallest possible plugs should be used;

(h) penetrometer tests are much simpler and quicker than vane tests and provide a full profile of the soil resistance;

(i) penetrometer tests should be more satisfactory than vane tests for 'in flight' site investigation, but proper correlations with the vane tests are necessary to provide reliable undrained strength profiles.

## 4. Mark II vane and penetrometer devices

### 4.1 Vane Mark II

Modifications to vane Mark I were devised to separate torques mobilized by blade and shaft and also to measure angular rotation.

A slip coupling close to the vane blade shown in fig.4.1 made possible a separation of the torques measured by blade and shaft. Measurements of angular rotation were performed by a rotary potentiometer connected to the vane shaft by two nylon gears.

Fig.4.2 presents results of vane tests carried out in three clay cakes with the following stress history:

(1) SI2A - The clay cake in fig.4.2a was subjected to $\sigma_v$ = 100 kPa and subsequently unloaded to zero pressure with drainage allowed;

(2) SI2B - The clay cake tested in fig.4.2b is the same described in (1) but reloaded to $\sigma_v$ = 125 kPa and then completely unloaded with no drainage being allowed;

(3) SI3 - The clay cake in fig.4.2c was consolidated in the laboratory to 140 kPa and subsequently mounted in the centrifuge. During pore pressure equilibrium 'in flight' overconsolidation ratio was induced varying from 10 at the depth of 10 mm to 1 at the depth of 210 mm and below. Tests shown in fig.4.2c were carried out after stopping the centrifuge. For all the three series of tests sufficient time was allowed for re-equilibrium of pore pressure after unloading.

Results in fig.4.2a,b for which clay cakes were subjected to a constant state of stress, show torques due to blades ($T_2$) almost constant with depth. On the other hand torques due to shaft frictions ($T_1$) increase with depth as expected. Results of the clay cake tested in fig.4.2c show values of T1, and consequently shear strengths, increasing with depth, which is a consequence of the stress history induced during the centrifuge test.

Fig.4.3 shows two typical records of vane tests in clay bed SI2B using the Mark II vane. It is clear that torques mobilized by the shaft increase with depth and that torques due to blade shear are almost constant.

Angles of rotation for peak torque measured with Mark II vane are shown in fig.4.4 for the three series of tests previously described. Values are almost constant with depth, the stiffer clay cake (test SI3) giving the lowest values. The consistent measurements in fig.4.4 when compared with scattered results in fig. 3.3 illustrate the accuracy of the new measurement system.

## 4.2 Cone penetrometer Mark II

Cone penetrometer Mark II has two load cells located at the extremities of the penetrometer, as shown in fig.4.5. The point resistance is measured by load cell I close to the cone tip, and the total load including side friction is recorded by load cell II. The strain gauges were arranged on the load cell to provide compensation for temperature and to make the load cells unaffected by bending stresses acting on the probe. This was accomplished by using two strain gauges in each arm of the full active bridge.

Fig.4.6 presents test plots for cones Mark I and Mark II in the same clay bed (SI2B) and at the same penetration rate of 1 mm/s. The following points should be noticed from this fig.: (a) the point resistance measured at the tip of cone Mark II ($q_{cI}$) is constant with depth, as expected; (b) the penetrometer resistance measured at the top of cone Mark II ($q_{cII}$)is considerably higher than the point resistance ($q_{cI}$); (c) the resistance due to penetration of cone Mark I ($q_{cIII}$) lay between values of $q_{cI}$ and $q_{cII}$.

Fig.4.7 presents penetrometer tests in clay beds SI2A and SI2B described earlier for different rates of penetration. Point cone resistances $q_{cI}$ and penetrometer resistances $q_{cII}$ have been plotted in different scales. It is evident that the point resistance $q_{cI}$ is less influenced by rate effects than the side friction which is proportional to $q_{cII} - q_{cI}$.

Values of $N_c$ from the three series of tests using Mark II devices presented in fig.4.8 are much lower than usually found in the literature for natural clays (see, for instance, Lunne and Kleven, 1981). This point is discussed further in the next section.

## 5. Tests using Mark II devices and piezocone

Detailed studies with the Mark II penetrometer and vane probes were carried out in Speswhite kaolin and Cambridge Gault clay to provide correlations between shear strength, point resistance and overconsolidation ratio. Kaolin and Gault clay have been lately used for centrifugal modelling of embankments on soft clays.

### 5.1 Experimental procedure

Specimen preparation and data acquisition followed the procedures described in section 3. For this series of tests the piston plugs of the consolidometer were modified to accommodate a small guide plug when tests were to be performed. This reduced stress relief close to the clay surface on removal of the plug. Vane and penetrometer tests followed the same procedures described earlier. The standard angular rotation of $72^{\circ}$/min was used for vane tests but for penetrometer tests further studies on the influence of the rate of penetrations were carried out.

Table 2 presents overburden pressure and other relevant consolidation data for kaolin and Gault clay specimens. Druck pore pressure transducers inserted at three depths in the clay cake through the consolidometer wall allowed monitoring of pore pressure changes. Vertical displacements were also measured. Complete equalization of pore pressures during swelling occurred in less than 12 hours for kaolin, but took 24 hours for Gault clay. The final thickness of the Gault clay cake was about two thirds of the kaolin cake. At least 24 hours was allowed after full dissipation of pore pressures before tests under the new overburden pressure were started. Kaolin cakes were prepared at OCR values of 1, 3 and 10 and Gault clay at OCR values of 1, 1.9 and 7. The maximum applied pressure for kaolin was 150 kPa and for Gault 126 kPa.

Vane tests were performed at five depths for each applied pressure and the range and average values of $c_u$ for the two clays are presented in tables 2.1 and 2.2. Averaged undrained strengths normalized by the vertical effective stresses are plotted against OCR in fig. 5.1. Also shown in fig. 5.1a are results of isotropic consolidated undrained triaxial tests carried out by Davidson (1980) in kaolin. The agreement between triaxial and vane tests is very good in spite of the differences of stress paths in the two kinds of tests. Normalized strengths of Gault clay presented in fig.5.1b are just under kaolin strength for OCR equal to one, but as OCR increases the strength of Gault clay becomes greater than the strength of kaolin at the same OCR.

**5.2 Penetrometer tests in kaolin**

Cone penetrometer values for kaolin are shown in fig. 5.2 and it can be seen that the influence of the rate of penetration decreases with OCR. The penetration rate has very little influence at OCR = 3 and 10. High et al (1979) also found similar effect for penetration tests in low plasticity reconstituted soil, for OCR varying between 1 and 7 and rates of penetration varying between 3 and 30 mm/min, which are about the same range of figures as for the studies here.

Penetrometer tests in kaolin were performed using cone Mark II and therefore the shaft load could be computed from the difference between the total load measured at the top and the load measured at the tip. Hence the side friction $f_s$ which is given by the shaft load divided by the shaft

area of the penetrometer could be computed. The ratio $f_s/q_c$ between the side friction and the point resistance is called friction ratio and is a useful parameter for soil classification in cone penetration practice. Tip and shaft loads, side friction and friction ratio for OCR equal to 10 are presented in fig.5.3 and 5.4 for tests with rates of penetration equal to 1mm/s and 20 mm/s, respectively.

Unlike the point resistance, the shaft friction seems to be more influenced by the rate of penetration. Consequently, the friction ratio is also influenced by the rate of penetration. In some of the tests, measurements of the total load were affected by friction in the guide plug and hence corresponding values of the side friction are not presented in table 3. Values of friction ratio vary between 2.1% and 3.8% which are typical for soft clay. A strict comparison with published field values is not in fact possible because friction measurements in the field are made over a standard length of shaft above the tip.

Table 3. also presents values of $N_c$ and $N_k$, as given by equations 3.2 and 3.3 computed from penetrometer and vane tests. Both values of $N_c$ and $N_k$ increase with OCR, but the increase in $N_k$ is less marked because of overburden effect reduces with increasing OCR. Values of $N_c$ and $N_k$ are plotted against OCR in fig.5.5. Values found by Francescon (1983) from model pile installation in kaolin, also plotted in fig.5.5, are lower than the values found here. The diameter of Francescon's pile was about twice the diameter of the penetrometer used here and his pile was provided with a $90^o$ truncated cone tip. Values of $N_c$ from pentrometer tests range from 4.5 at OCR = 1 to 10 at OCR = 10 and $N_k$ ranges from 9 at OCR = 1 to 11 at OCR = 10. These values are lower than usually found in field tests (Lunne and Kleven, 1981).

It is possible that measured point resistances are being reduced by pore pressures acting at the base of the cone, due to unequal end area at the cone tip, as pointed out by Campanella and Robertson(1981). Assuming magnitude of pore pressure generated during penetration being as big as $q_c$, which is possible, corrected point resistances for penetrometer Mark II would be about 36% bigger than measured $q_c$. However increased values of $N_c$ would still be considerably lower than values observed in the field. It appears that more studies are necessary to clarify these points.

## 5.3 Piezocone tests in Gault clay

A piezocone probe has been developed to measure simultaneously point resistance and pore pressure during penetration. It has not yet been used in the centrifuge but will be available for future tests. The value of the piezocone for in situ investigation of clay foundations has been pointed out by several research workers (e.g., Baligh et al, 1980; Roy et al, 1982). The ability to evaluate the coefficient of consolidation during dissipation tests is an important feature of this instrument.

The miniature piezocone is shown in fig.5.6. It is mounted with a rosette load cell located at the top of the penetrometer. A stiff internal rod transmits the load carried by the tip to the top load cell. The four webs of the load cell are subjected to bending stresses and produce signal outputs which are ten times higher than the ones produced by the load cells used in penetrometer Mark II. The rosette load cell was provided with a full bridge circuit with two strain gauges in each arm of the bridge and compensated for temperature effects.

The porous element was located at the tip of the piezocone, as this gave the simplest design. There is some discussion among geotechnical specialists about the best location of the porous element. It is out of the scope of this paper to discuss advantages and disadvantages of each position, for which the reader is referred to Roy et al (1982). The pore pressure transducer used in the piezocone was a PDCR 81 Druck pressure transducer which ensures very fast response time when properly deaired. The deairing was done under vacuum and this proved to be very satisfactory.

Reconstituted Gault clay was consolidated to $\sigma_v$ = 126 kPa and vane tests were performed as described earlier(see table 2.1). Complete swelling was then allowed to the pressures of 66 and 18 kPa and vane tests were also carried out. Tests with the piezocone were carried out at the same pressures but during reloading back to 126 kPa.

Table 4 summarizes results obtained with the piezocone at different penetration rates. For overconsolidation ratios greater than one, values of point resistance and pore pressure are not much influenced by variations in penetration rate between 1 and 20 mm/s; but for OCR equal to one both point resistance and pore pressure are smaller at a penetration rate of 0.20 mm/s than at 4 mm/s. The pore pressure seems to be more

affected than the point resistance by the difference of rate of penetration. This is reflected in the ratio $\Delta u/q_c$ equal to 0.94 for 0.20 mm/s and 1.05 for 4 mm/s. These tests for OCR equal to 1 are presented in fig.5.7. Tests for OCR equal to 3 and 7 are presented in fig.5.8 and 5.9 respectively, and illustrate the points previously made. Roy et al (1982) found very small rate effects on pore pressure measurements for piezocone tests in St Albans clay. It is apparent that effects of the rate of penetration on pore pressures and point resistances are dependent on the type of soil.

The variations of pore pressure response with the rate of penetration for the shallower depths in fig.5.9 suggest that for that particular set of tests the porous element was not well deaired. However in all tests pore pressures reached a plateau of constant values.

Variations of $N_c$ and $N_k$ with OCR for Gault clay are presented in table 4 and fig.5.10 . The values are considerably higher than for kaolin and are in the range usually obtained for natural clays. Reasons why quantitative values of $N_c$ and $N_k$ for kaolin differ so much from Gault clay are not very clear. However both sets of values increase with OCR but $N_c$ being more dependent on OCR than $N_k$. This trend has also been observed for tests in kaolin.

Variations of pore pressures with OCR are presented in fig.5.11. Pore pressures are normalized against undrained strength, $\Delta u/c_u$ [1] vertical effective stresses, $\Delta u/\bar{\sigma}_v$, and point resistance $\Delta u/q_c$. The same trend and similar values were obtained by Francescon (1983) for tests in kaolin. The tip pore pressure in Francescon's pile was measured on a truncated cone tip as opposed to the tip of 60° cone used here. Values of $\Delta u/c_u$ vary between 15 and 13 compared to Francescon's values of between 12 and 10. Values of $\Delta u/\bar{\sigma}_v$ for Gault clay vary between 3 and 10.7 compared to kaolin values between 2.5 and 9.5. Values of $\Delta u/q_c$ for Gault vary between 1.05 and 0.95 and for kaolin between 1.14 and 1.00. It can be concluded that normalized pore pressures in Gault clay are similar in magnitude to those in kaolin.

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[1] Note $c_u$ measured during unloading of clay cake but $\Delta u$ measured during reloading.

It has been proposed that the ratio between pore pressure and point resistance could be used to estimate the OCR. Baligh et al (1980) have proposed the ratio $u/q_c$ in which u is the total pore pressure, whereas Campanella and Robertson (1981) suggested the ratio $\Delta u/q_c$. Since here ambient pore pressures are negligible, the two ratios are virtually the same. Results found here for Gault clay as well as results found by Francescon (1983) for kaolin suggest that the ratio $\Delta u/q_c$ is not strongly dependent on OCR. Similar evidence for another kaolin clay was found by Smits (1982). Further experimental studies should be carried out to clarify this point, since field evidence of the usefulness of the $u/q_c$ ratio have been presented (see also Tumay et al, 1981; Lacasse and Lune, 1982).

Observations of the decay of pore pressures after stopping the penetrometer were performed for the three overburden pressures and are shown in fig.5.12a. The same results are normalized in fig.5.12b. Values of $t_{50}$ decrease with increase of OCR. This is consistent with the observed increase of the coefficient of consolidation $c_v$ with OCR. Experimental evidence (Francescon, 1983) has shown that the coefficient of consolidation during pore pressure dissipation around piles and cones is representative of swelling stress paths. Moreover numerical analyses carried out by Baligh and Levadoux (1980) for cones in cross anisotropic material have shown that the coefficient of horizontal consolidation $c_h$ governs the process. Therefore backfigured values of the coefficient of consolidation with the piezocone should be treated as $c_h$ for unloading-reloading.

Results of dissipation tests allow computation of $c_h$ by using closed form analytical solutions for radial consolidation of cylindrical and spherical cavities in isotropic elastic soils. Such solutions are given by Randolph and Wroth (1979) for cylindrical cavities and Baligh and Levadoux (1980) for cylindrical and spherical cavities. It is usually assumed that the initial excess pore pressure varies linearly with the logarithm of the radius, as field and laboratory tests have shown (Randolph and Wroth,1979;Francescon, 1983).

An adequate solution for dissipation of pore pressures at the tip of a $60^\circ$ cone is likely to be somewhere between spherical and cylindrical solutions. In order to model the two-dimensional consolidation problem

around a $60^{\circ}$ cone, Baligh and Levadoux (1980) used a linear uncoupled finite element program (i.e. based on Terzaghi-Rendulic theory). The initial distribution of normalized pore pressures prior to consolidation, fig.5.13, was obtained from a steady state solution developed by Levadoux and Baligh (1980) for normally consolidated Boston Blue clay. Randolph et al (1978) investigated the nonlinear consolidation around pile shafts and concluded that pore pressure dissipation was not significantly affected by soil nonlinearities.

Baligh and Levadoux (1980) applied their solution not only to Boston Blue clay but also to the Connecticut Valley Varved clay. For Boston Blue clay $c_h$ computed from dissipation tests was found to be very close to $c_v$ for unloading, backfigured from in-situ pore pressure measurements. Satisfactory results were also obtained for the Connecticut clay.

Time factors at the tip of a $60^{\circ}$ cone given by the Baligh and Levadoux (1980) solution are presented in Table 5 for a number of degrees of consolidation. The time factor is defined as

$$T = \frac{c_h \cdot t}{R^2} \qquad (5.1)$$

where R is the radius of the cone shaft. Also presented in table 5 are computed values of $c_h$ for each degree of consolidation. Table 6 presents values of $c_v$ computed from the reloading of the clay specimen together with values of $c_h$ backfigured from dissipation tests. The close agreement between $c_v$ and $c_h$ indicates that the reconstituted Gault clay is not anisotropic with respect to values of coefficient of consolidation. Similar agreement was obtained by Lacasse and Lunne (1982) for Onsoy and Drammen clays, also using Baligh and Levadoux's solution.

Fig.5.14 compares predicted numerical dissipation curves by Levadoux's solution with experimental curves assuming $c_h$ computed from 50% dissipation. The agreement is good and improves as OCR increases. Good agreement at high OCR is perhaps unexpected since the solution was developed for lightly overconsolidated clays. Observed differences in the early stages of dissipation arise mostly from the assumption of constant $c_h$ in the finite element solution. As seen in Table 5 $c_h$ is higher for U less than 40% but becomes fairly constant after this.

Other solutions to interpret dissipation tests are available, as mentioned earlier. It is interesting to compare time factors given by Levadoux's solution with others to appreciate the differences. Levadoux's solution for a $60^{\circ}$ cone gives $T_{50} = 3.65$ for the cone tip, as shown in Table 5. Closed form solutions for cylindrical and spherical cavities for logarithm initial excess of pore pressures (and $\lambda = 10$ as defined by Baligh and Levadoux, 1980) give $T_{50}$ equal to 1.8 and 3.0 respectively. The method proposed by Tortenson (1977) gives $T_{50}$ equal to 0.8 and 1.4 for spherical and cylindrical solutions respectively, assuming $G/c_u$ equal to 100. Therefore it can be concluded that the use of methods other than the one proposed by Baligh and Levadoux (1980) would underestimate values of $c_h$. The overall agreement between measurements and predictions seem to show that Baligh and Levadoux's method is very satisfactory.

## 6. Conclusions

It is important to measure clay strength during centrifuge tests rather than after stopping the centrifuge. Negative pore pressures generated after stopping the centrifuge draw any free water into the clay and may also cause air entry or cavitation. Consequently clay strengths measured after stopping the centrifuge are significantly lower than in flight values.

Vane and penetrometer equipments Mark I have been developed to perform site investigation during centrifuge tests. Tests in laboratory using these early devices were performed to investigate a number of aspects of vane and penetrometer testing in reconstituted kaolin clay. Influence of factors such as vane geometry, vane rotation rate and time between stopping and rotating the vane were investigated. Influence of the rate of penetration in penetrometer tests were also investigated. An important conclusion of these studies was that significant shaft friction was affecting results of both vane and penetrometer tests.

Improved Mark II vane and Mark II penetrometer were designed as a result of previous programmes of testing. In the Mark II vane the rotation rate was measured directly and the torque due to shaft friction was separated from the torque due to the blades. The Mark II cone was provided with a load cell at the tip to measure point resistance and a load cell at

the top to measure the total load. The side friction could be estimated by the difference between the measurements of the two load cells. Improvements in values of vane strength and point resistance were illustrated using equipment Mark II.

Detailed programmes of tests in kaolin and Gault clay were undertaken to provide correlations between shear strength, point resistance, overburden pressure and overconsolidation ratio. It was also expected that some factors affecting vane and penetrometer testing would be clarified. The conclusions achieved were:

(a) a rotation rate of $72^{\circ}$/min should be adopted for vane tests in kaolin;

(b) the variation of the vane strength with OCR for kaolin agrees with undrained strength measured in isotropic consolidated triaxial tests;

(c) in kaolin and Gault clays the rate of cone penetration does not have significant influence on the point resistance and this influence is reduced as the overconsolidation ratio reduces;

(d) the rate of penetration has some influence on the side friction; although this influence was not demonstrated to decrease with increasing OCR, such a trend similar to the point resistance would be expected;

(e) empirical cone factors $N_c$ and $N_k$ were shown to increase with OCR. Values of $N_c$ were shown to be more dependent on OCR than $N_k$;

(f) values of $N_c$ for reconstituted kaolin appear to be much lower than for natural soils. Values of $N_c$ and $N_k$ for Gault clay are higher than for kaolin;

(g) it appears that more studies on cone penetration resistances of reconstituted soils are necessary.

A piezocone probe capable of measuring simultaneously pore pressures and point resistance was developed. Tests with the piezocone in Gault clay showed that pore pressures developed during penetration do not seem to be dependent on variations in the rate of penetration between 1 and 20 mm/sec. Variations of normalized pore pressures developed during penetration with OCR were observed to have the same trend and similar

magnitude obtained by other research workers.

Dissipation tests were carried out with the piezocone in Gault clay. Computations of the horizontal coefficient of consolidation $c_h$ for Gault clay were performed based on the numerical method proposed by Baligh and Levadoux (1980) which takes into account the geometry of the $60^o$ cone. The values of $c_h$ computed using $T_{50}$ were shown to be very close to values of $c_v$ computed from reloading of the clay specimens. Therefore it appears that reconstituted Gault clay is isotropic with respect to the coefficient of consolidation.

Overall agreement between theoretical and experimental curves of degree of dissipation against time factor were obtained. Time factors for experimental curves were computed with $c_h$ obtained from Baligh and Levadoux's solution for 50% degree of consolidation.

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Table 1: Geometry of the vanes (after Cheah, 1980)

| VANE | d(mm) | h(mm) | t(mm) |
|---|---|---|---|
| A | 19 | 28 | 1.0 |
| B | 18 | 14 | 1.0 |
| C | 27 | 14 | 1.5 |
| D | 36 | 14 | 2.0 |

d = vane diameter

h = vane height

t = thickness of vane blades

Table 2: Consolidation data for specimens tested

2.1 - Speswhite kaolin (LL = 69%; PL = 38%; PI = 31%)

water content of slurry = 122.0%

water content at end of test = 53.2%

height of slurry = 515 mm

height of clay cake at 150 kPa = 292 mm

| $\sigma'_v$ (kPa) | OCR | $c_u$ (kPa) | | $c_u/\sigma'_v$ |
|---|---|---|---|---|
| | | range | average | |
| 150 | 1 | 33 - 35.3 | 33.9 | 0.226 |
| 50 | 3 | 18.6 - 22.4 | 21.6 | 0.432 |
| 15 | 10 | 15 - 17.2 | 16.0 | 4.067 |

2.2 - Gault clay (LL = 60%; PL = 25%; PI = 35%)

water content of slurry = 89.2%

water content at end of test = 42.6%

height of slurry = 304 mm

height of clay cake at 126 kPa = 189 mm

| $\sigma'_v$ (kPa) | OCR | $c_u$ (kPa) | | $c_u/\sigma'_v$ |
|---|---|---|---|---|
| | | range | average | |
| 126 | 1 | 24.2 - 27.8 | 25.4 | 0.202 |
| 66 | 1.9 | 18.6 - 20.8 | 20.8 | 0.315 |
| 18 | 7 | 14.8 - 18.2 | 16.5 | 0.92 |

Table 3: Penetrometer tests in kaolin

| OCR | $\sigma'_v$ (kPa) | $c_u$ (kPa) | p. rate (mm/s) | $q_c$ (kPa) | $f_s$ (kPa) | $f_s/q_c$ (%) | $N_c$ | $N_k$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 150 | 33.9 | 1 | 295 | - | - | 4.9 | 8.7 |
| | | | 6 | 290 | - | - | 4.1 | 8.6 |
| | | | 20 | 310 | - | - | 4.7 | 9.1 |
| 3 | 50 | 21.6 | 1 | 230 | - | - | 8.3 | 10.7 |
| | | | 4 | 230 | - | - | 8.3 | 10.7 |
| | | | 20 | 240 | 8.6 | 3.8 | 8.8 | 11.1 |
| 10 | 15 | 16.0 | 1 | 180 | 3.8 | 2.1 | 10.3 | 11.3 |
| | | | 20 | 170 | 6.6 | 3.6 | 9.7 | 10.6 |

Table 4: Piezocone tests in Gault clay

| OCR | $\sigma'_v$ (kPa) | $c_u$ (kPa) | p. rate (mm/s) | $q_c$ (kPa) | $\Delta u$ (kPa) | $N_c$ | $N_k$ | $\Delta u/c_u$ | $\Delta u/\sigma'_v$ | $\Delta u/q_c$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 126 | 25.4 | 0.20 | 325 | 305 | 7.8 | 12.8 | 12.0 | 2.42 | 0.94 |
| | | | 4 | 360 | 380 | 9.2 | 14.1 | 14.9 | 3.01 | 1.05 |
| 1.9 | 66 | 20.8 | 4 | 300 | 300 | 11.2 | 14.4 | 14.4 | 4.54 | 1.0 |
| | | | 20 | 295 | 285 | 11.0 | 14.2 | 13.7 | 4.31 | 0.97 |
| 7 | 18 | 16.5 | 1 | 250 | 210 | 14.1 | 15.1 | 12.7 | 11.7 | 0.84 |
| | | | 6 | 255 | 230 | 14.4 | 15.5 | 13.9 | 12.8 | 0.86 |
| | | | 20 | 245 | 210 | 13.7 | 14.8 | 12.7 | 11.7 | 0.90 |

Table 5: Dissipation tests for Gault clay

| | | | | OCR = 1 | | OCR = 1.9 | | OCR = 7.0 | |
|---|---|---|---|---|---|---|---|---|---|
| U % | $\bar{u}$ | T | $R^2T$ ($mm^2$) | t (s) | $c_h$ ($m^2/s$) | t (s) | $c_h$ ($mm^2/s$) | t (s) | $c_h$ ($mm^2/s$) |
| 20 | 0.8 | 0.44 | 17.74 | 8 | 2.21 | 9.5 | 1.86 | 6.7 | 2.64 |
| 40 | 0.6 | 1.90 | 76.61 | 90 | 0.851 | 68 | 1.12 | 40 | 1.91 |
| 50 | 0.5 | 3.65 | 147.18 | 190 | 0.77 | 140 | 1.05 | 80 | 1.84 |
| 60 | 0.4 | 6.5 | 262.1 | 340 | 0.77 | 270 | 0.97 | 150 | 1.74 |
| 80 | 0.2 | 27 | 1089 | 1150 | 0.95 | 1000 | 1.09 | 680 | 1.60 |

Table 6: Coefficient of consolidation for Gault clay

| $\sigma'_v$ (kPa) | OCR | coefficient of consolidation ($mm^2/s$) | |
|---|---|---|---|
| | | $c_h$ (dissipation tests) | $c_v$ (reloading) |
| 18 | 7 | 1.84 | - |
| 66 | 1.9 | 1.05 | 1.03 |
| 126 | 1 | 0.77 | 0.78 |

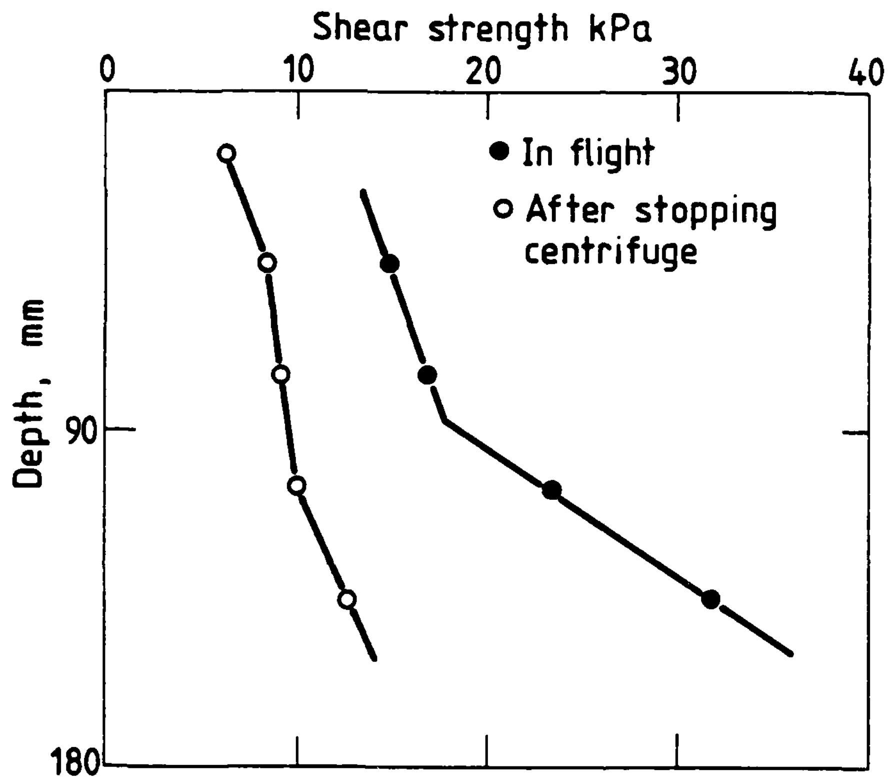



Fig. 1.1: Measured vane strengths during flight and after stopping centrifuge (after Davies, 1981)

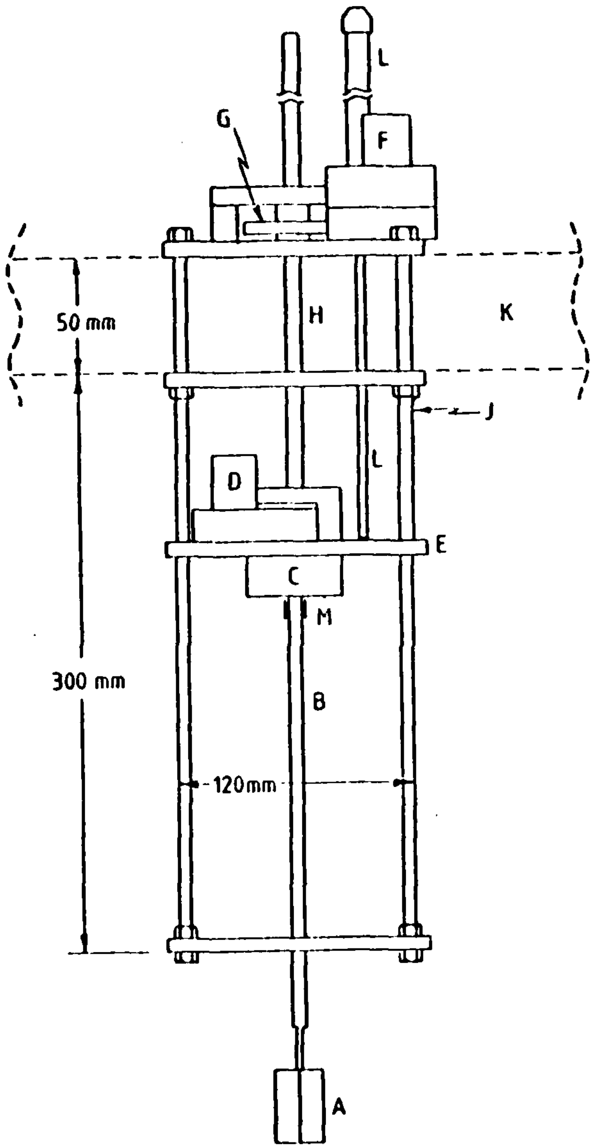



Fig. 2.1: Vane apparatus Mark I
(after Davies, 1981)

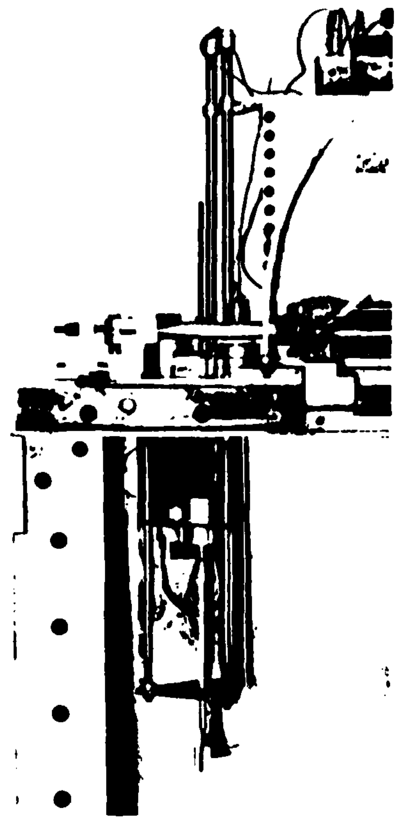


Fig. 2.2: Vane apparatus Mark I
mounted in centrifuge package

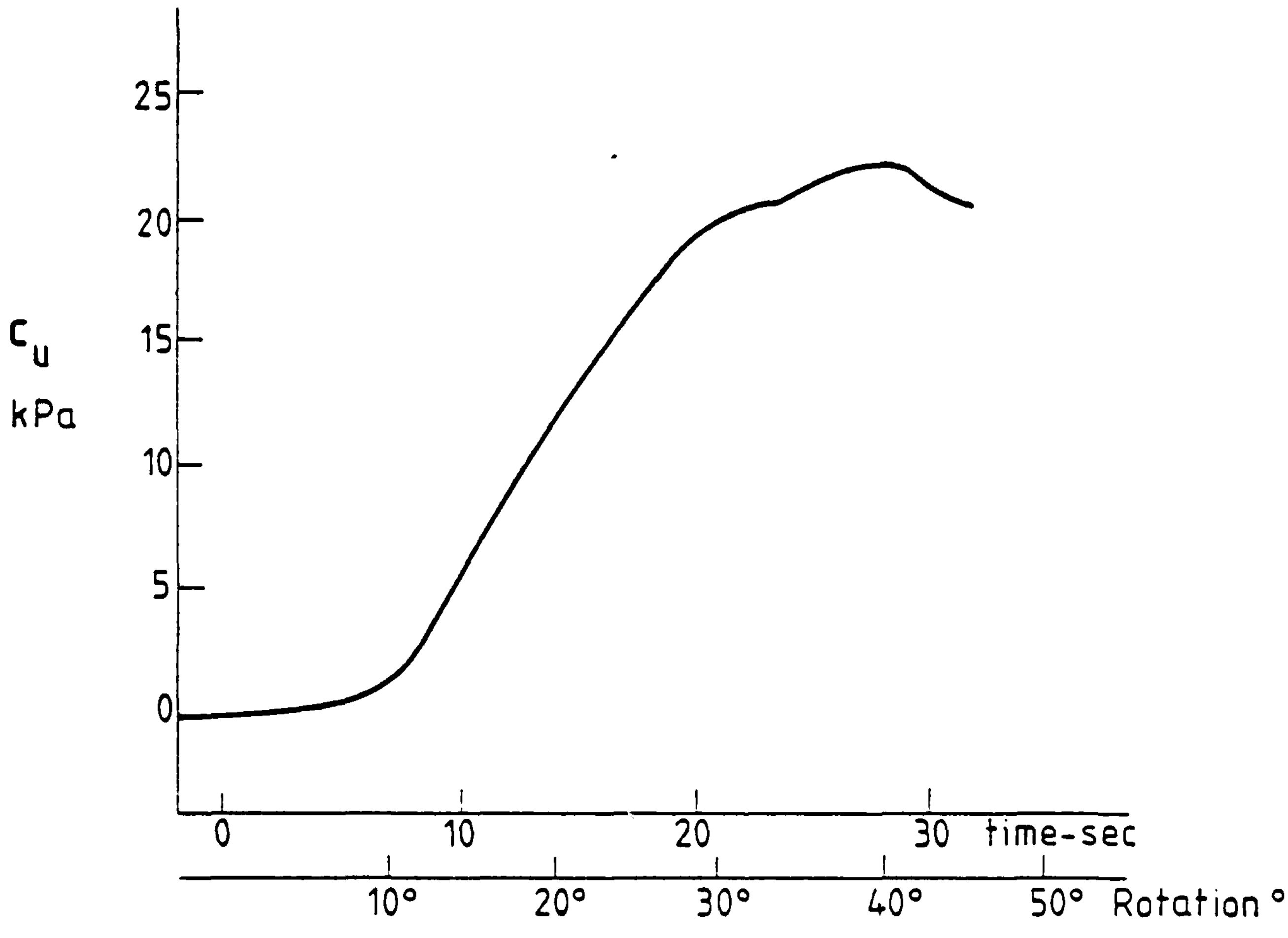



Fig. 2.3: Typical vane record (after Davies, 1981)

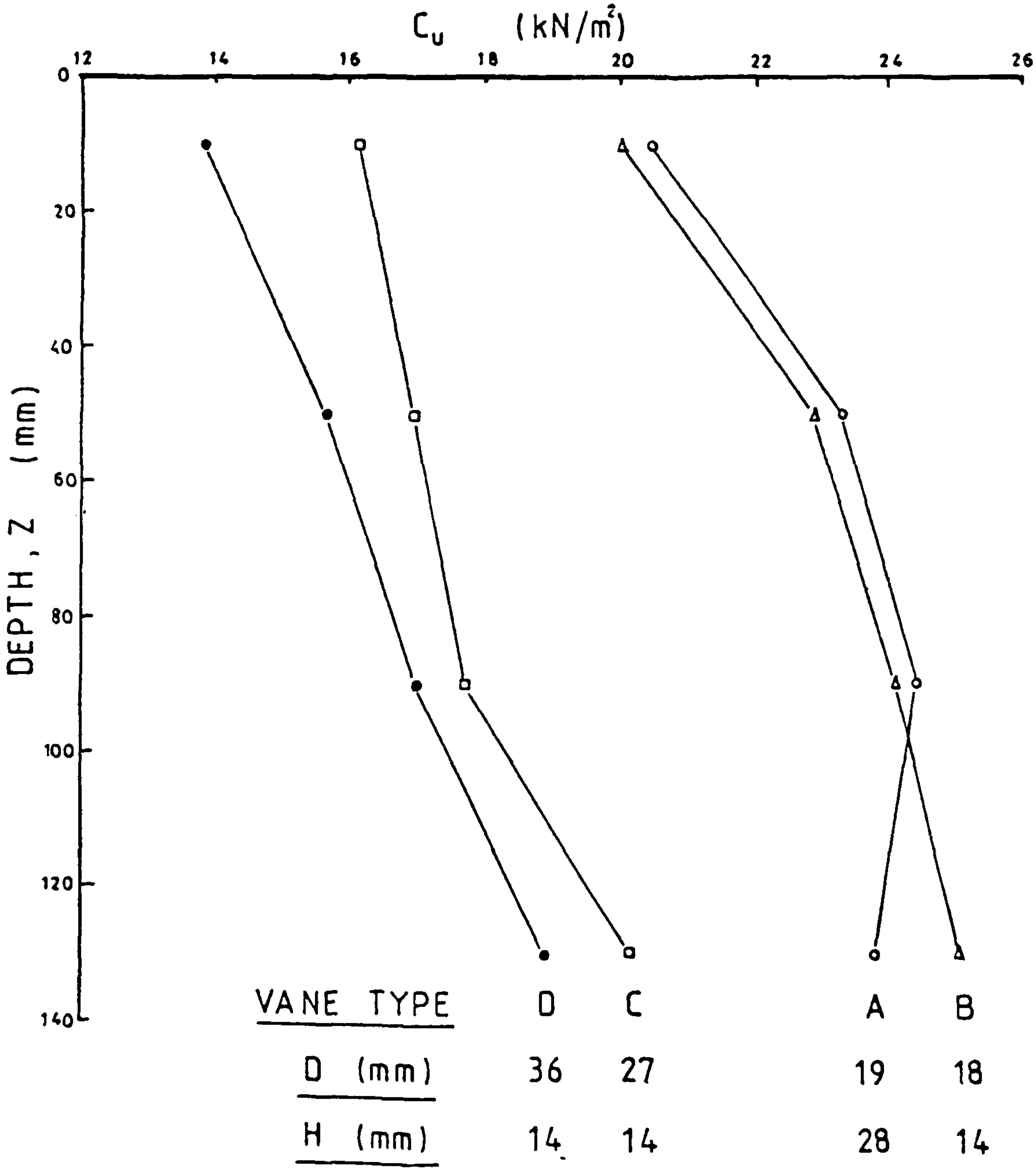



Fig. 2.4: Influence of the vane geometry on clay strength (after Cheah, 1981)

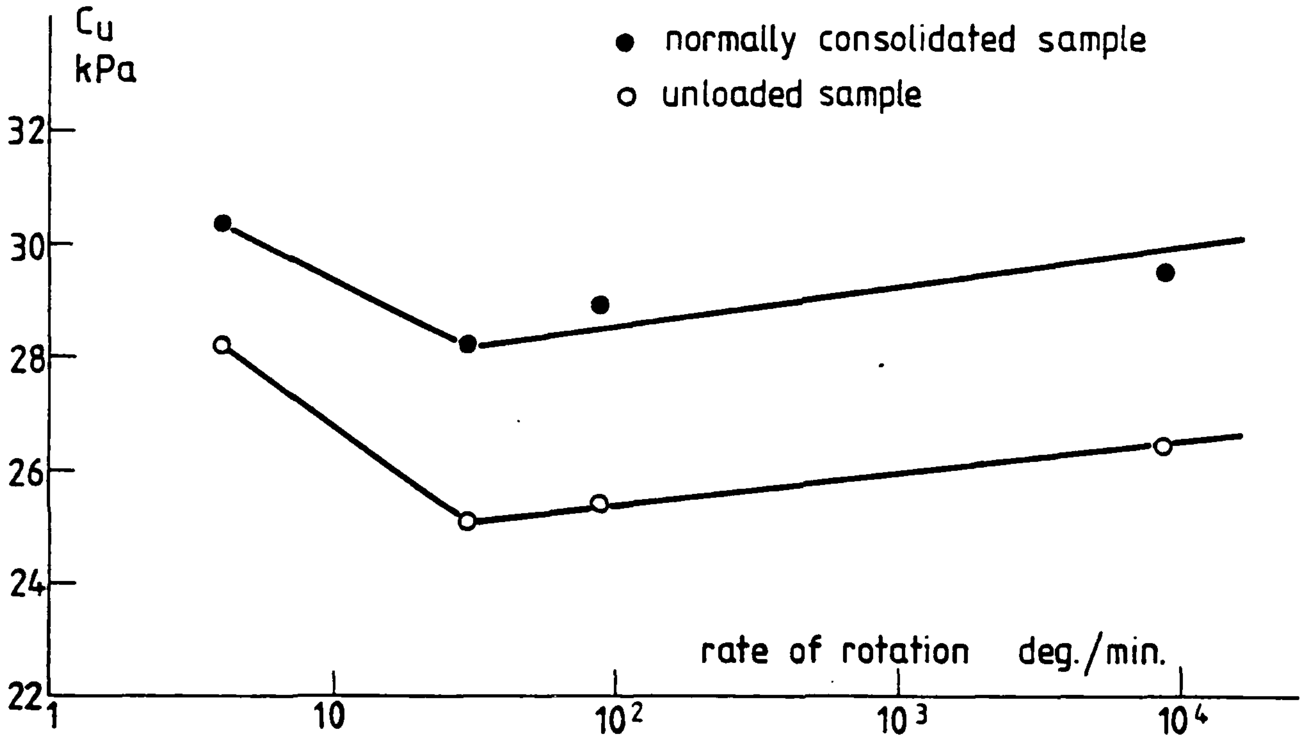



Fig. 2.5: Variation of measured vane shear strength with rate of rotation (after Cheah, 1981)

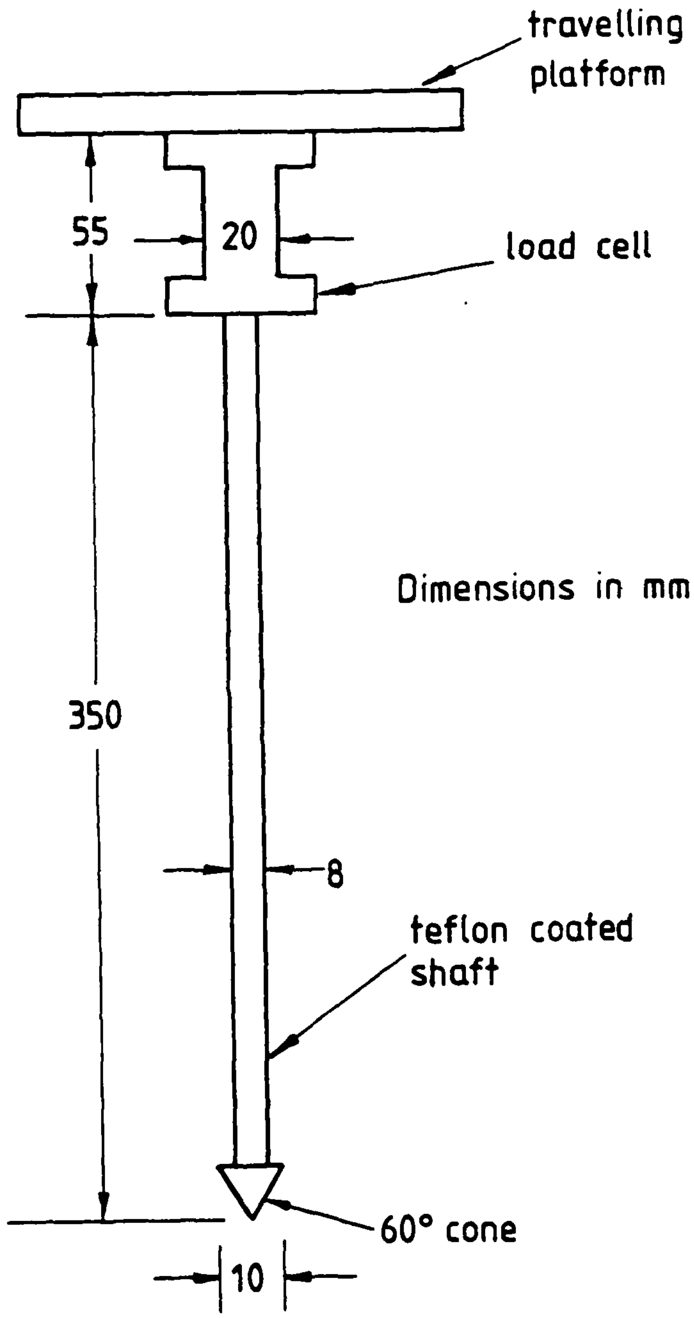



Fig. 2.6: Cone penetrometer Mark I

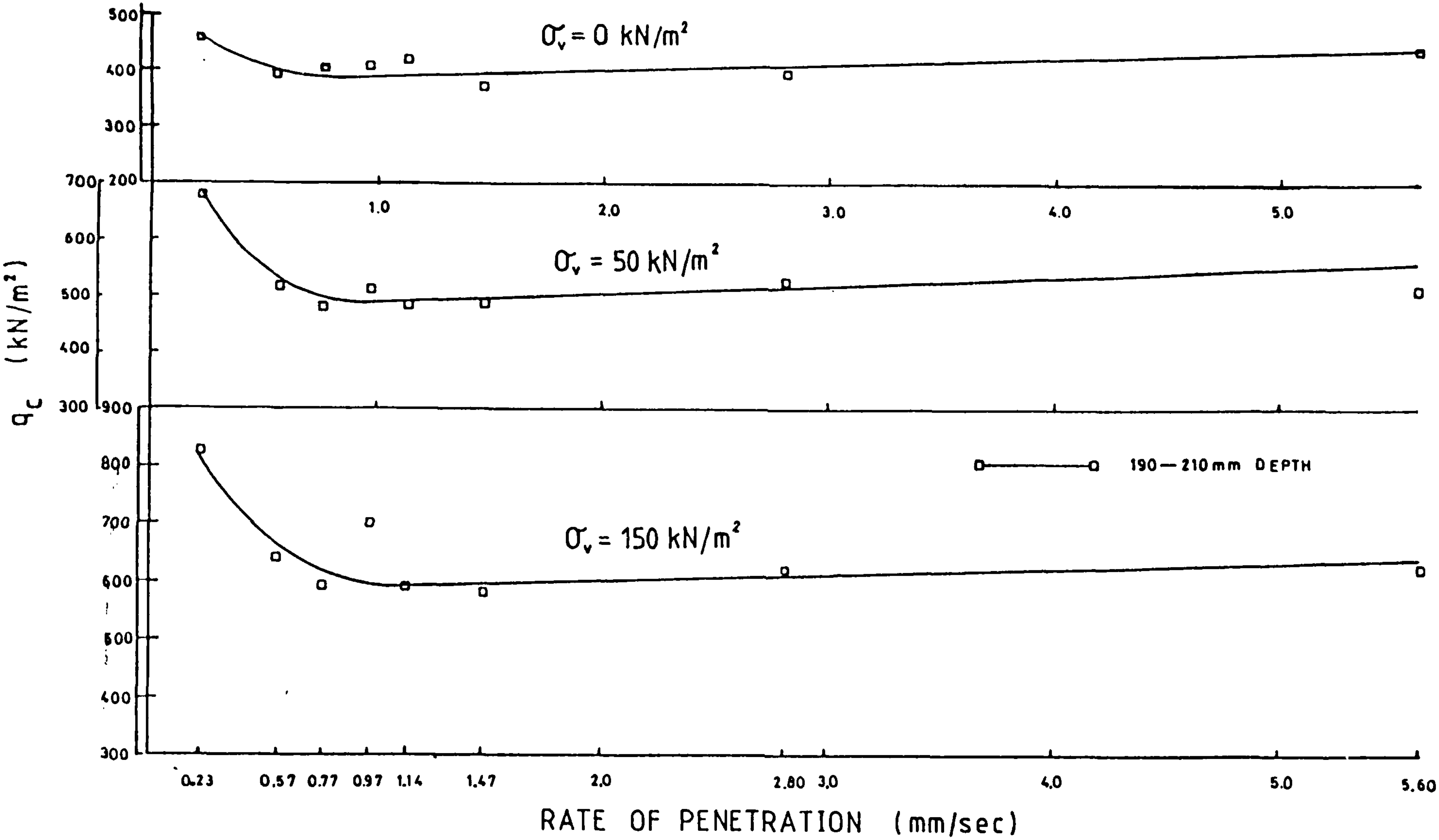



Fig. 2.7: Variation of penetrometer resistance with rate of penetration

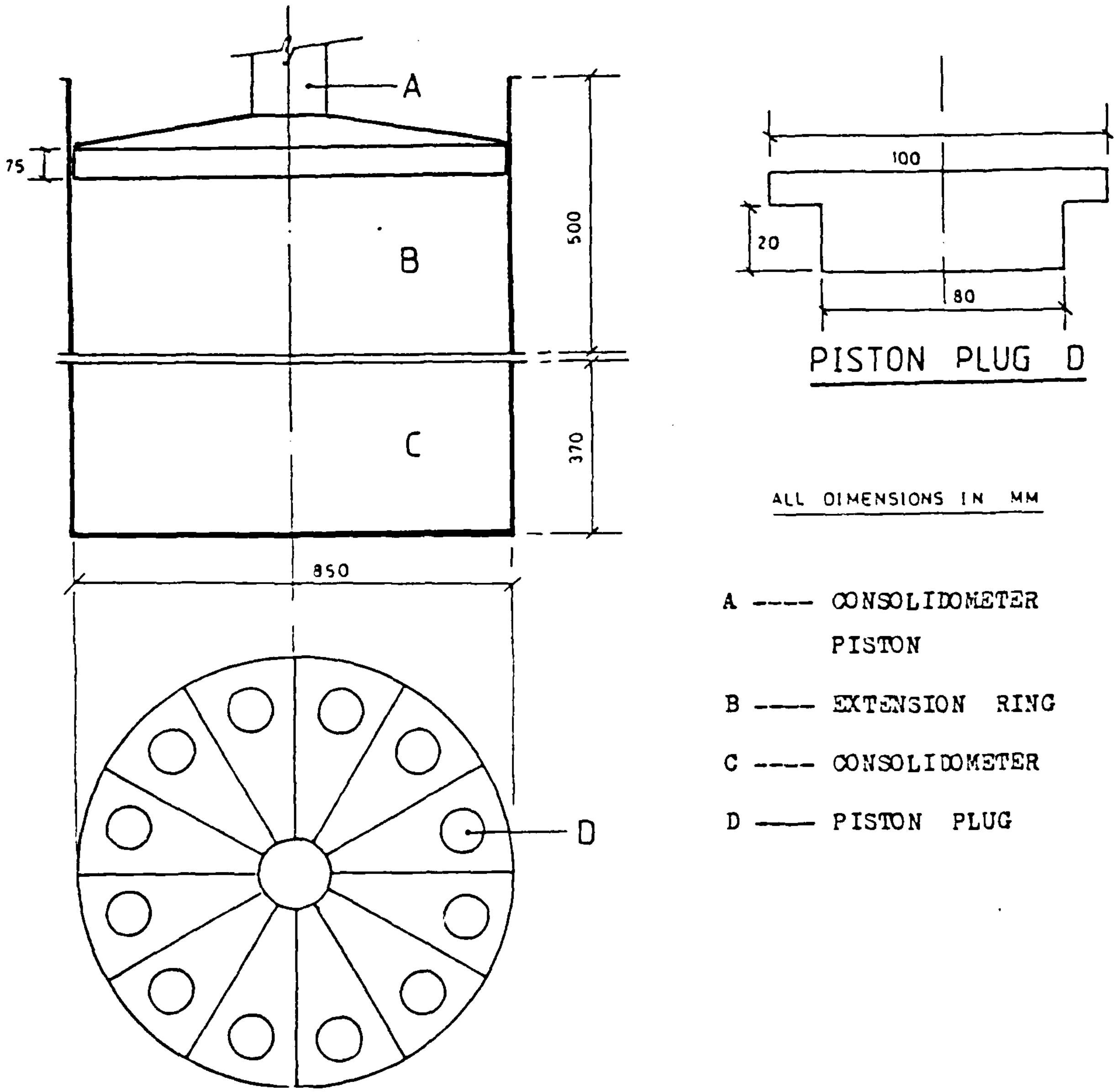



Fig. 3.1: Consolidometer and piston plug

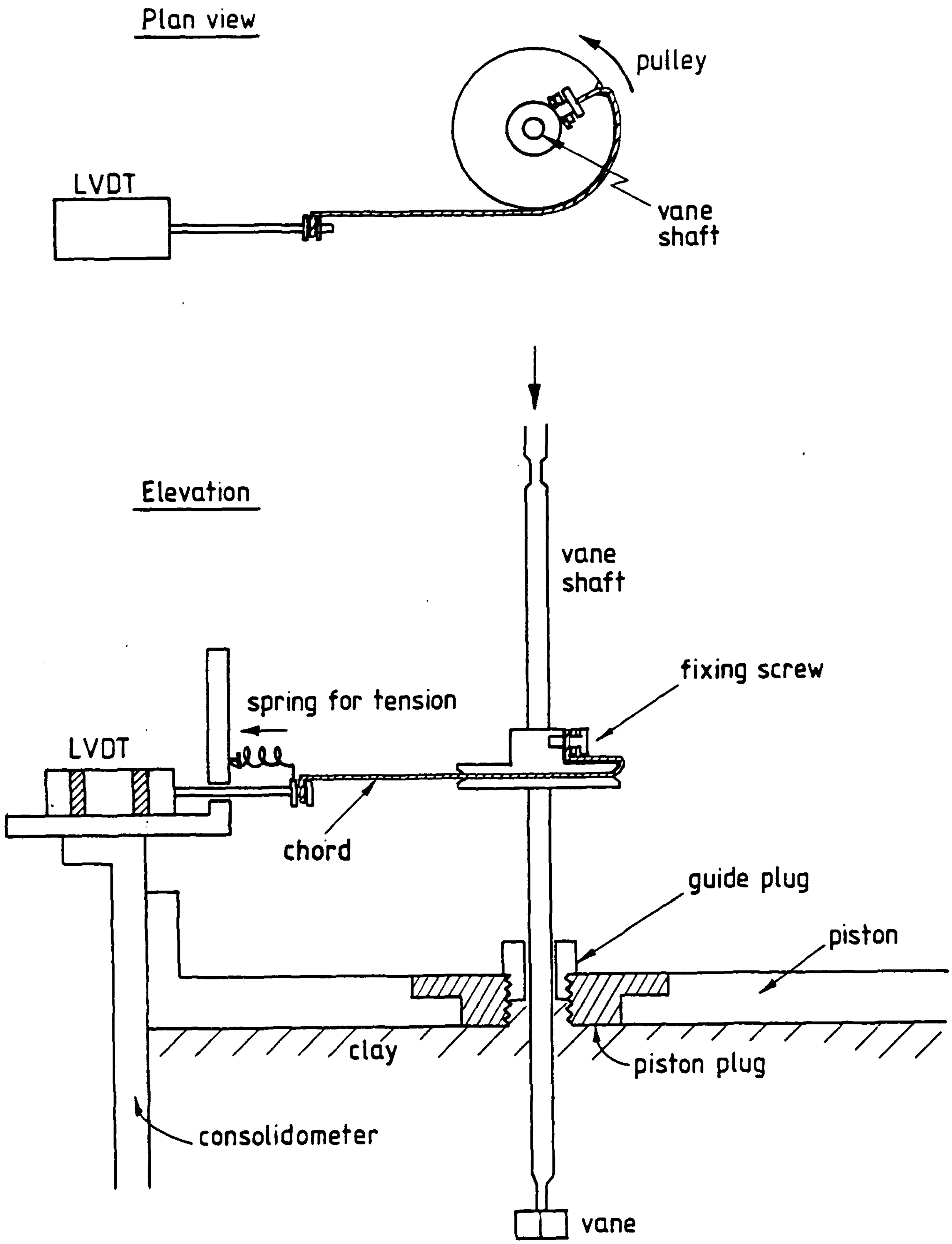



Fig. 3.2: Device to measure the angle of rotation

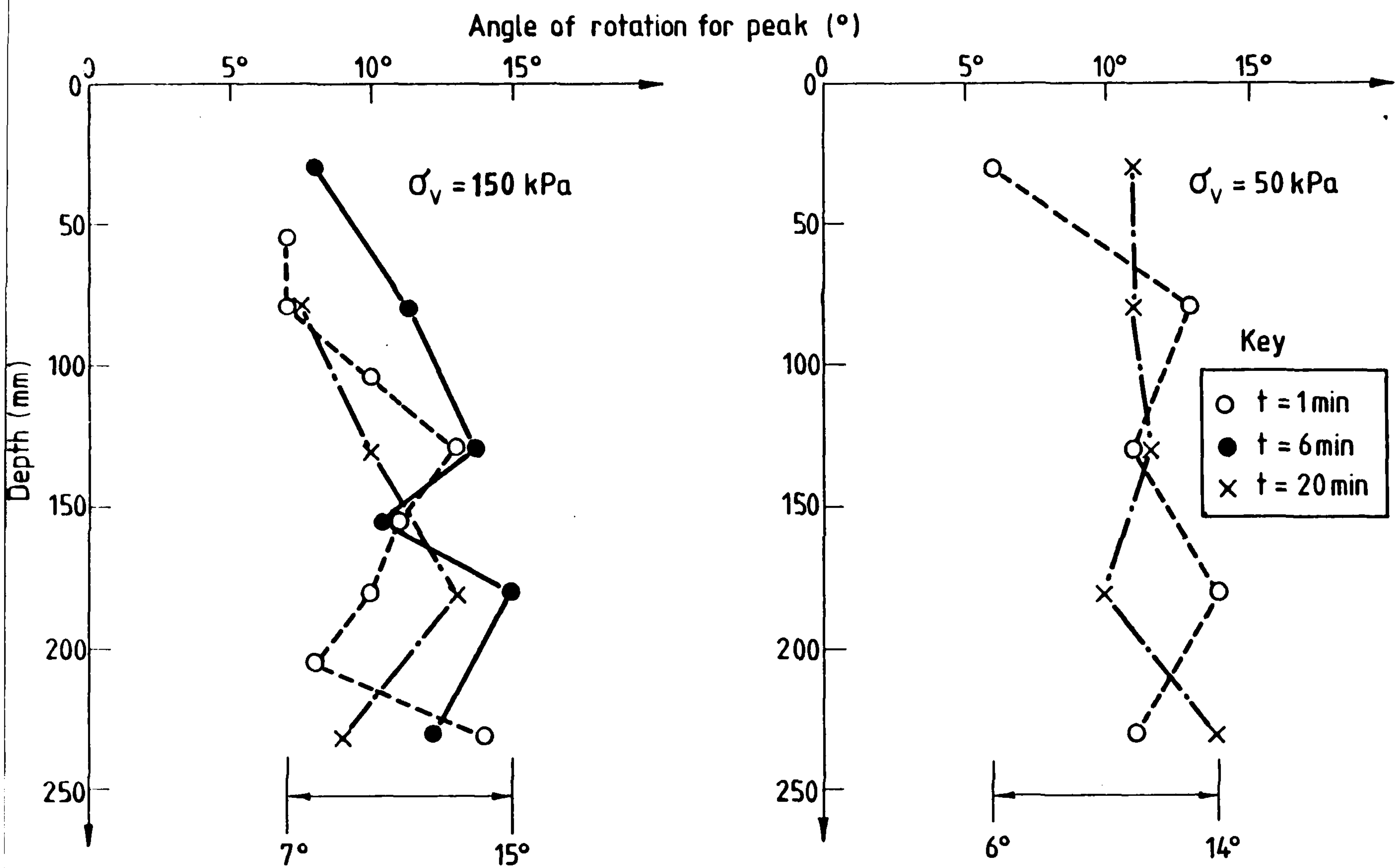



Fig. 3.3: Angle of rotation for peak

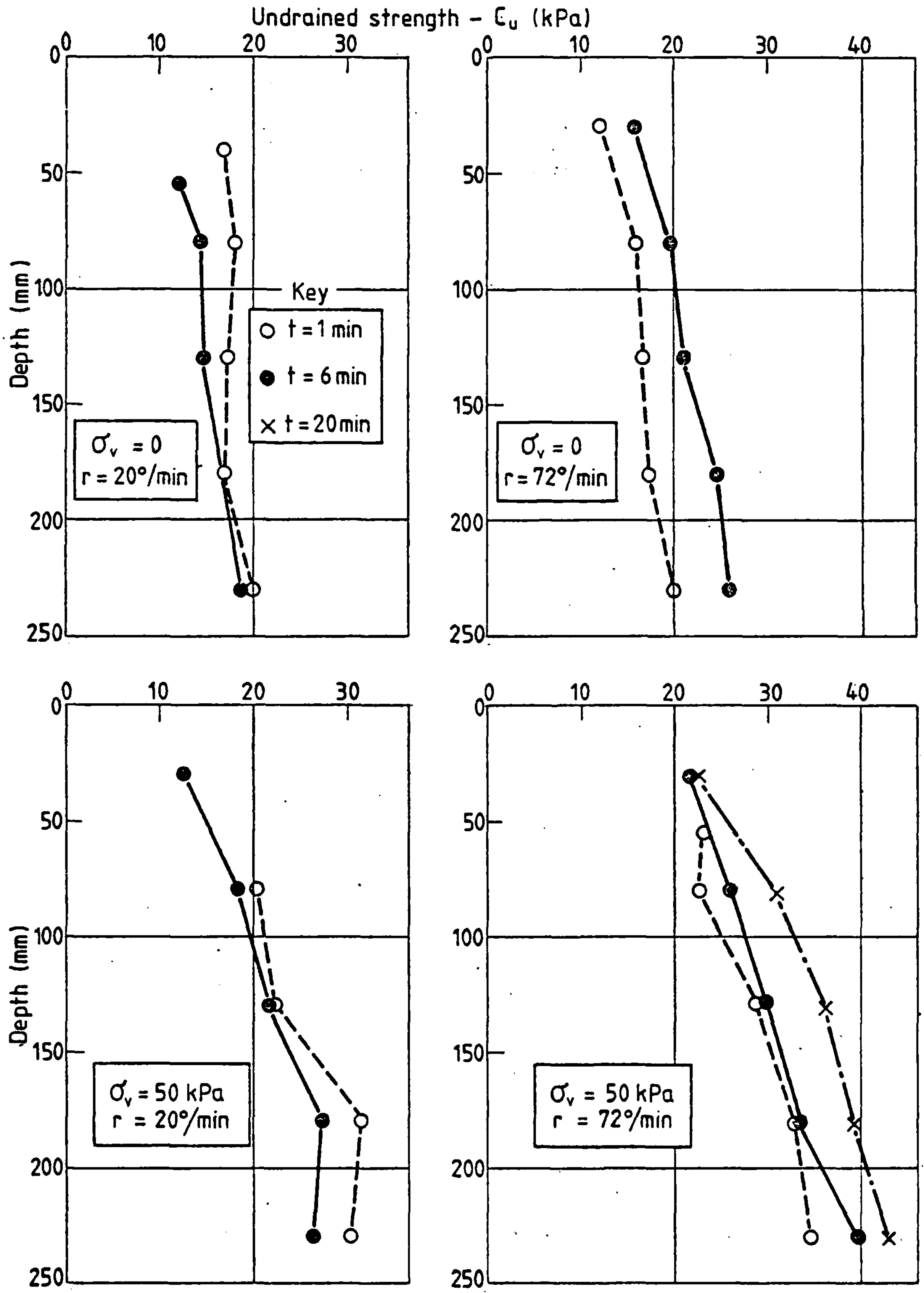



Fig. 3.4: Variation of the clay strength with time for test

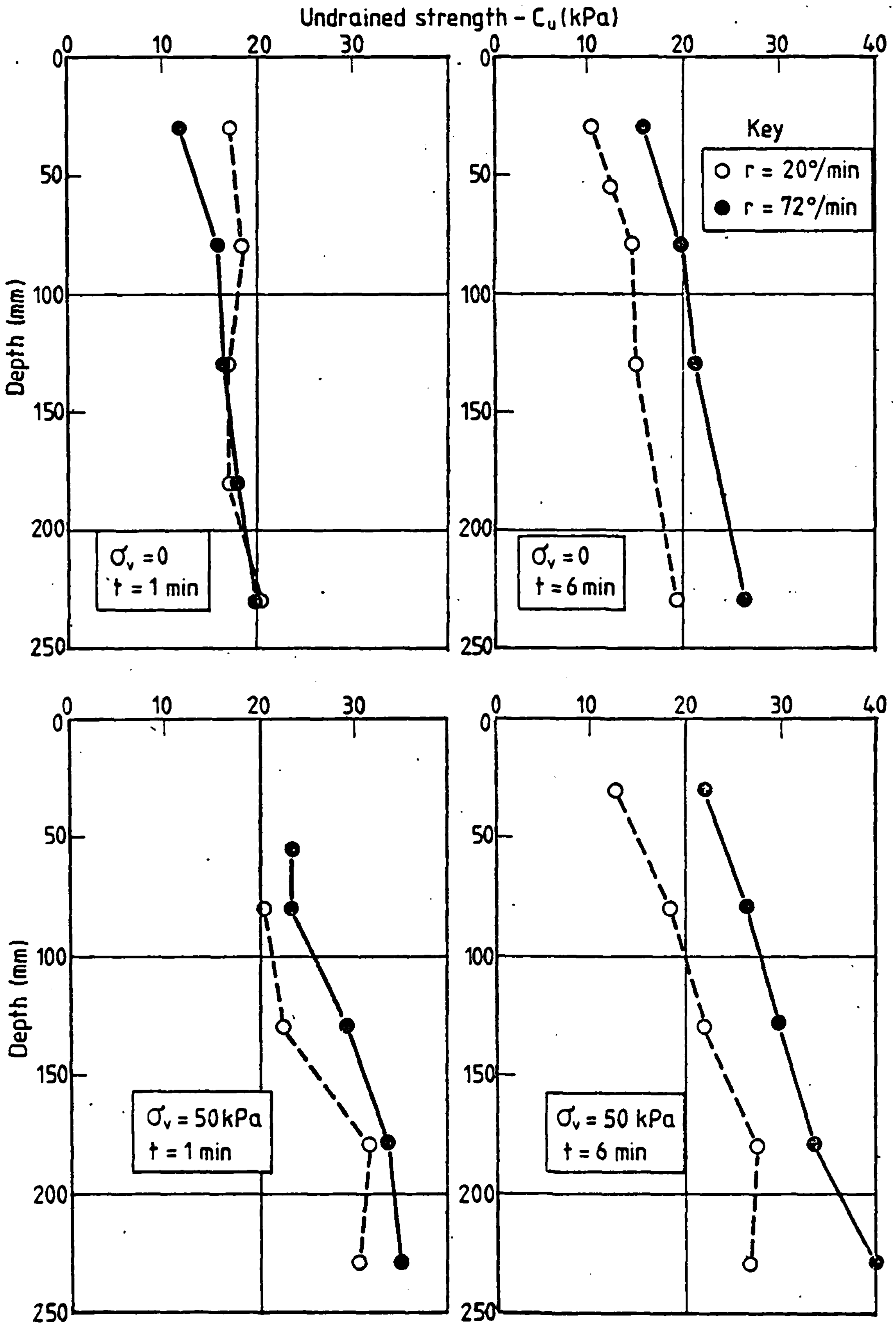



Fig. 3.5: Variation of the clay strength with rate of rotation

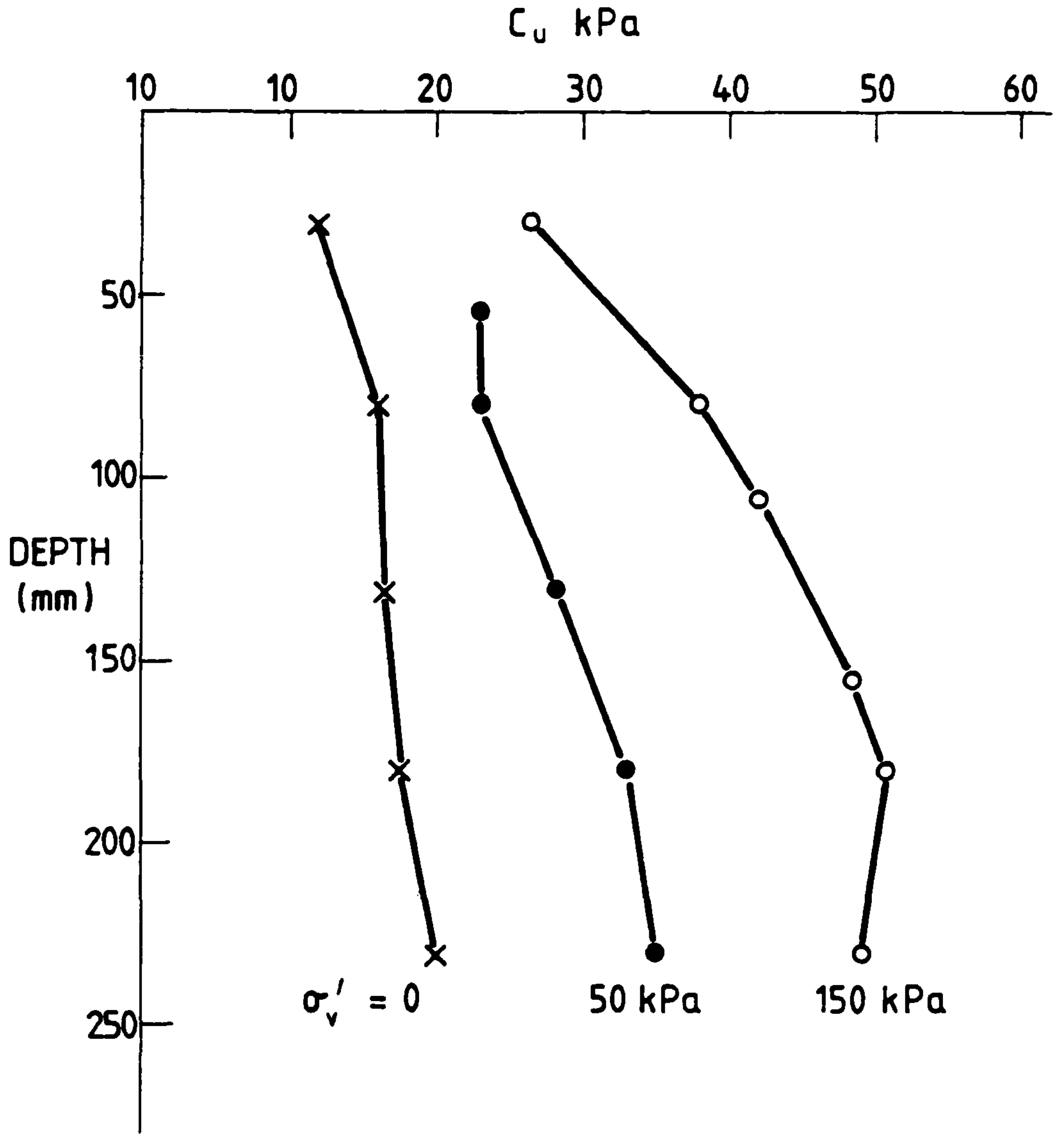



Fig. 3.6: Variation of the clay strength with overburden pressure and depth - vane Mark I

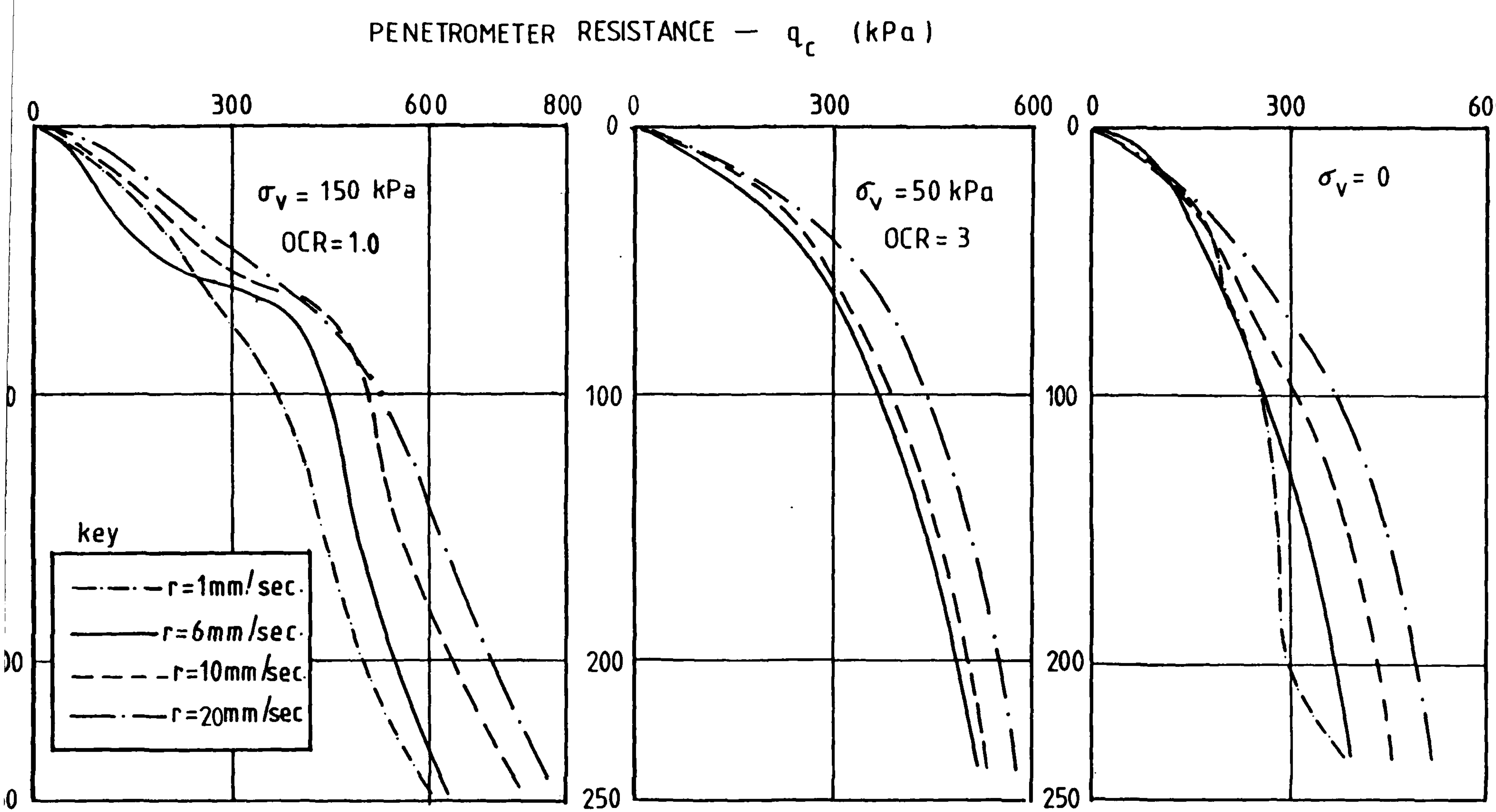



Fig. 3.7: Variation of the penetrometer resistance with rate of penetration for penetrometer Mark I

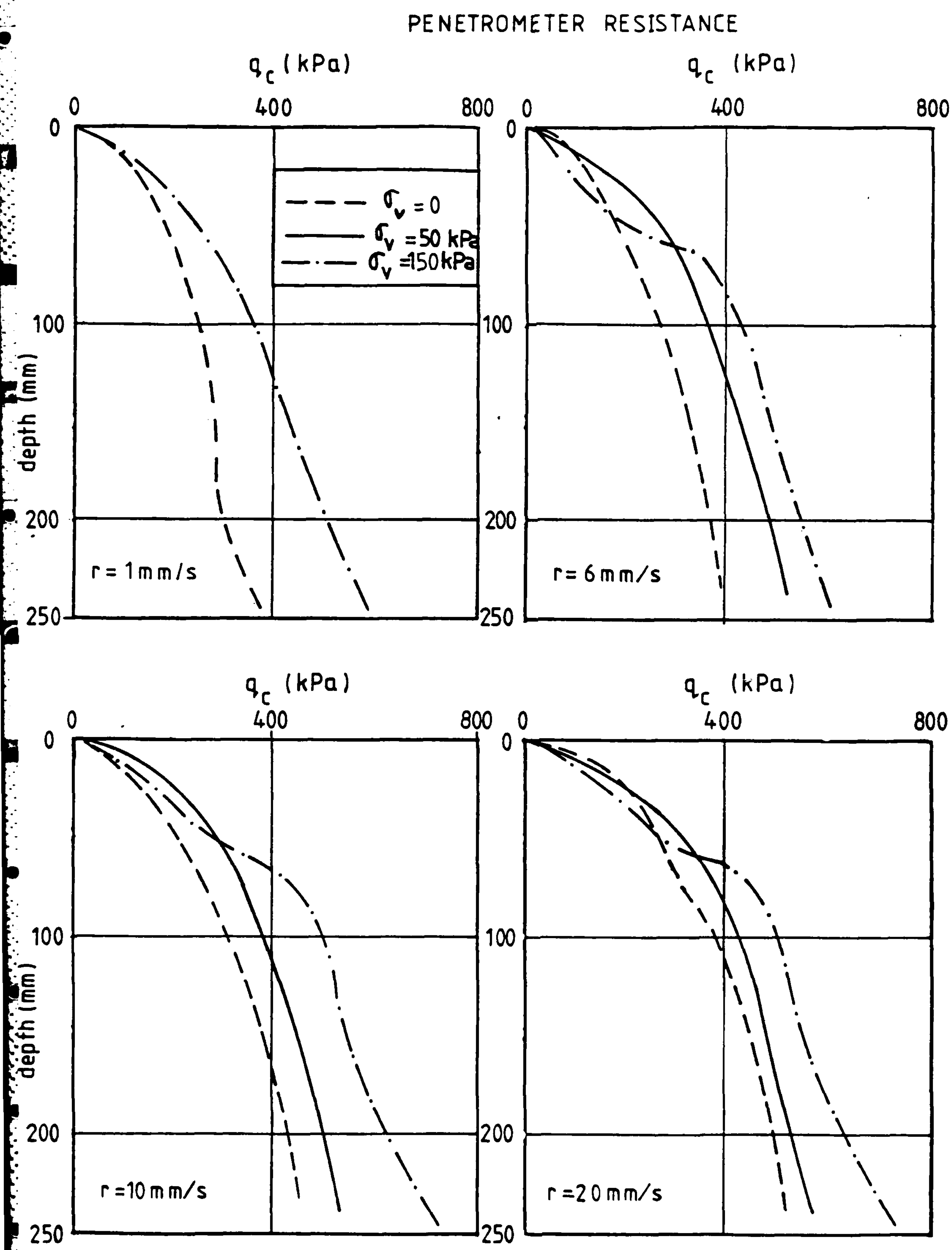
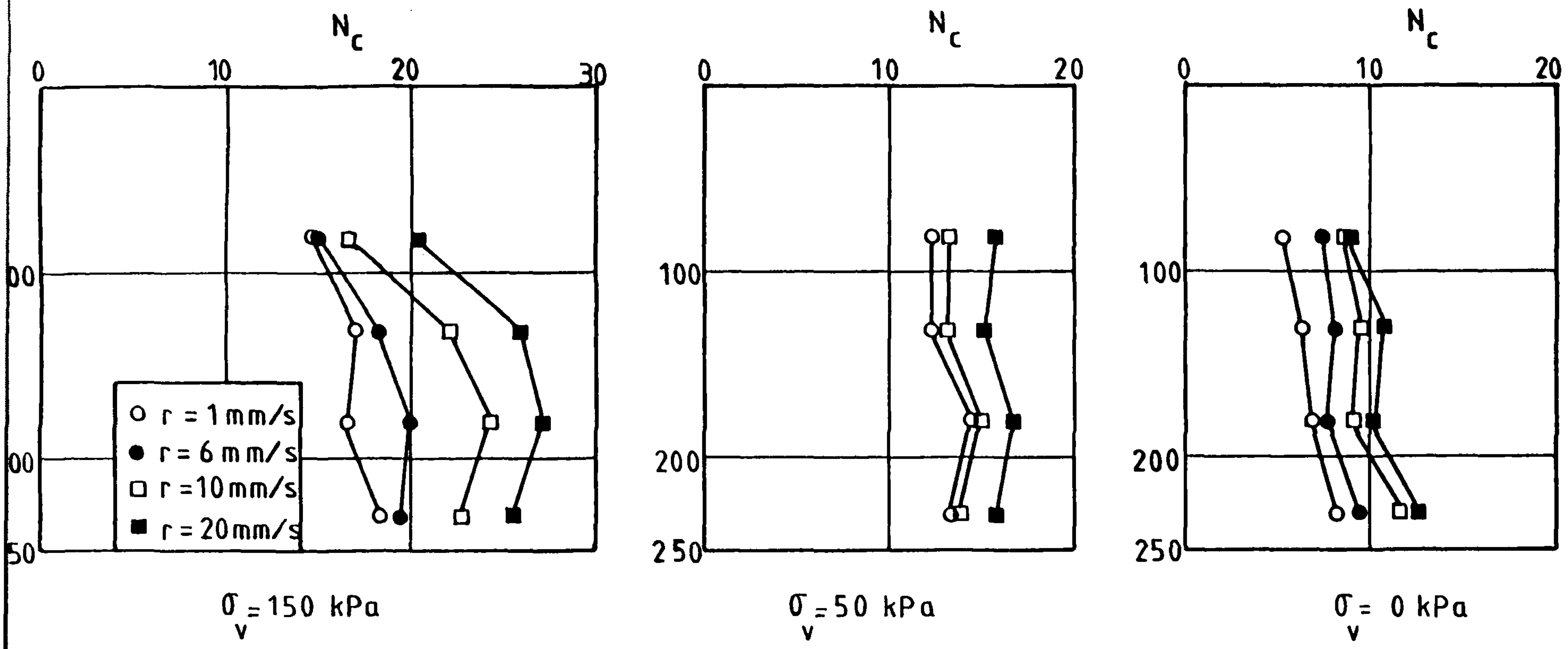



Fig. 3.8: Variation of the penetrometer resistance with overburden pressure for penetrometer Mark I




$$N_c = \frac{q_c - \sigma_v}{c_u}$$

Fig. 3.9: Correlation between penetrometer resistance and vane strength using Mark I devices

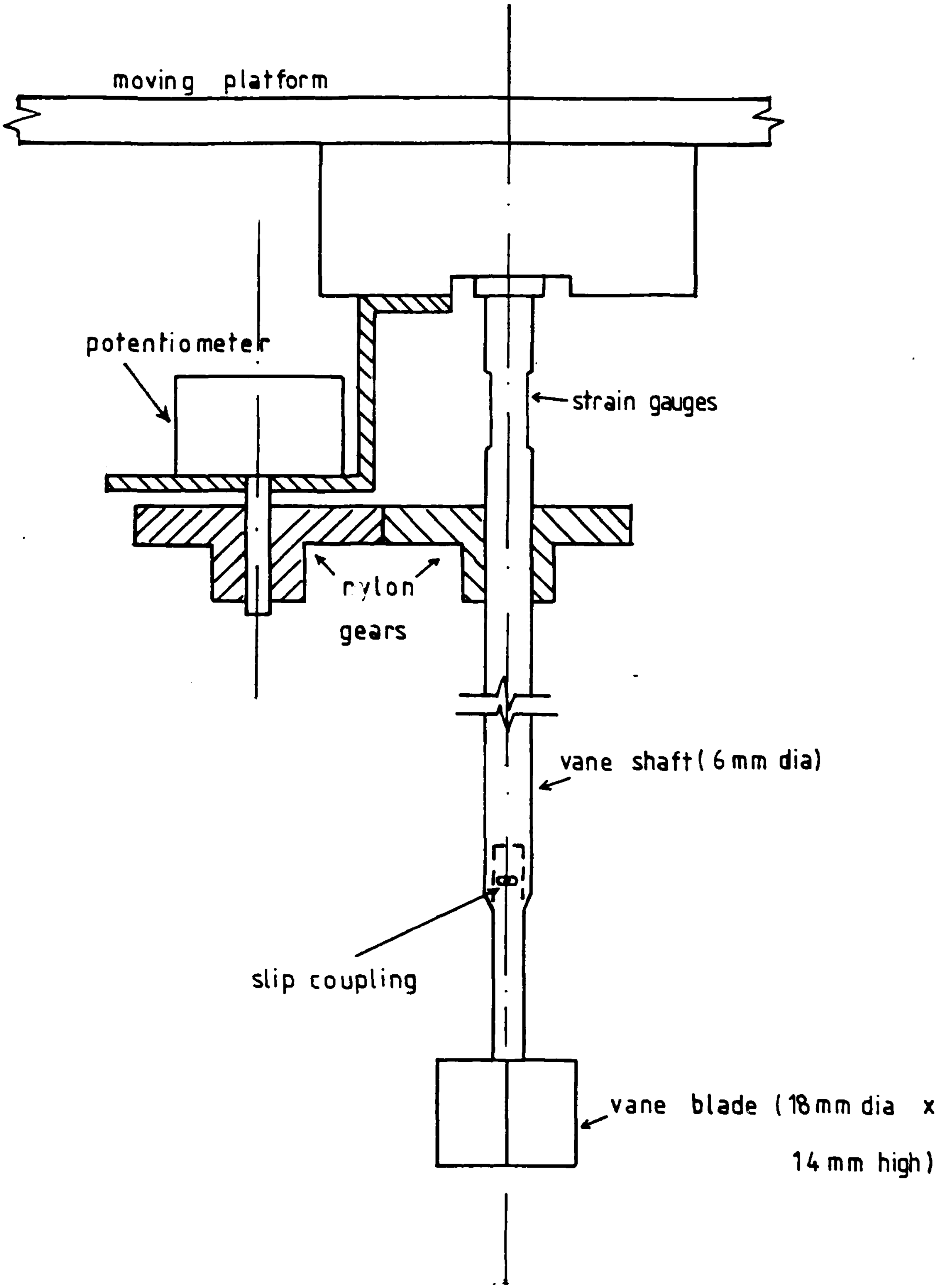



Fig. 4.1: Vane apparatus Mark II

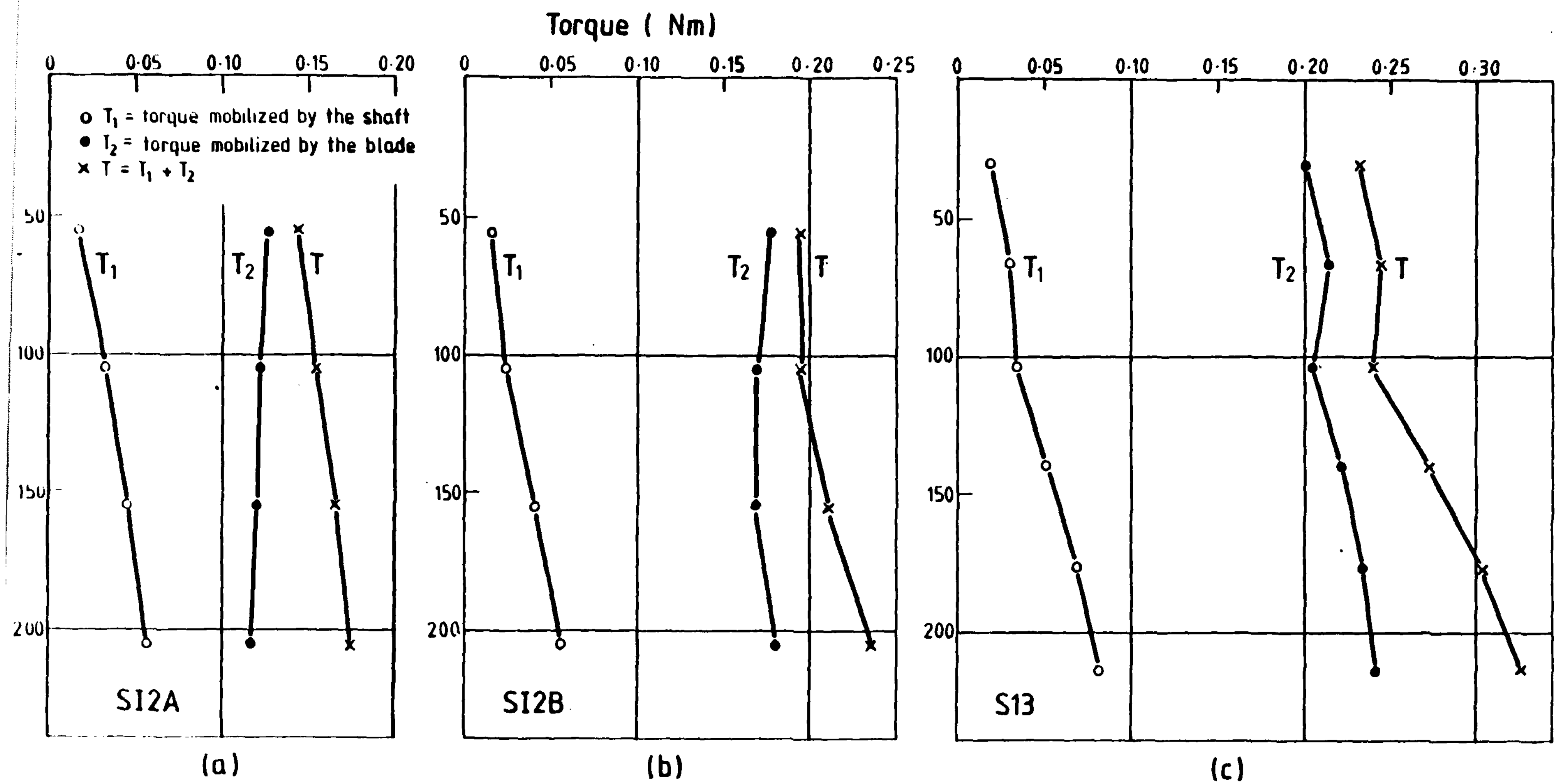



Fig. 4.2: Measurements with vane Mark II

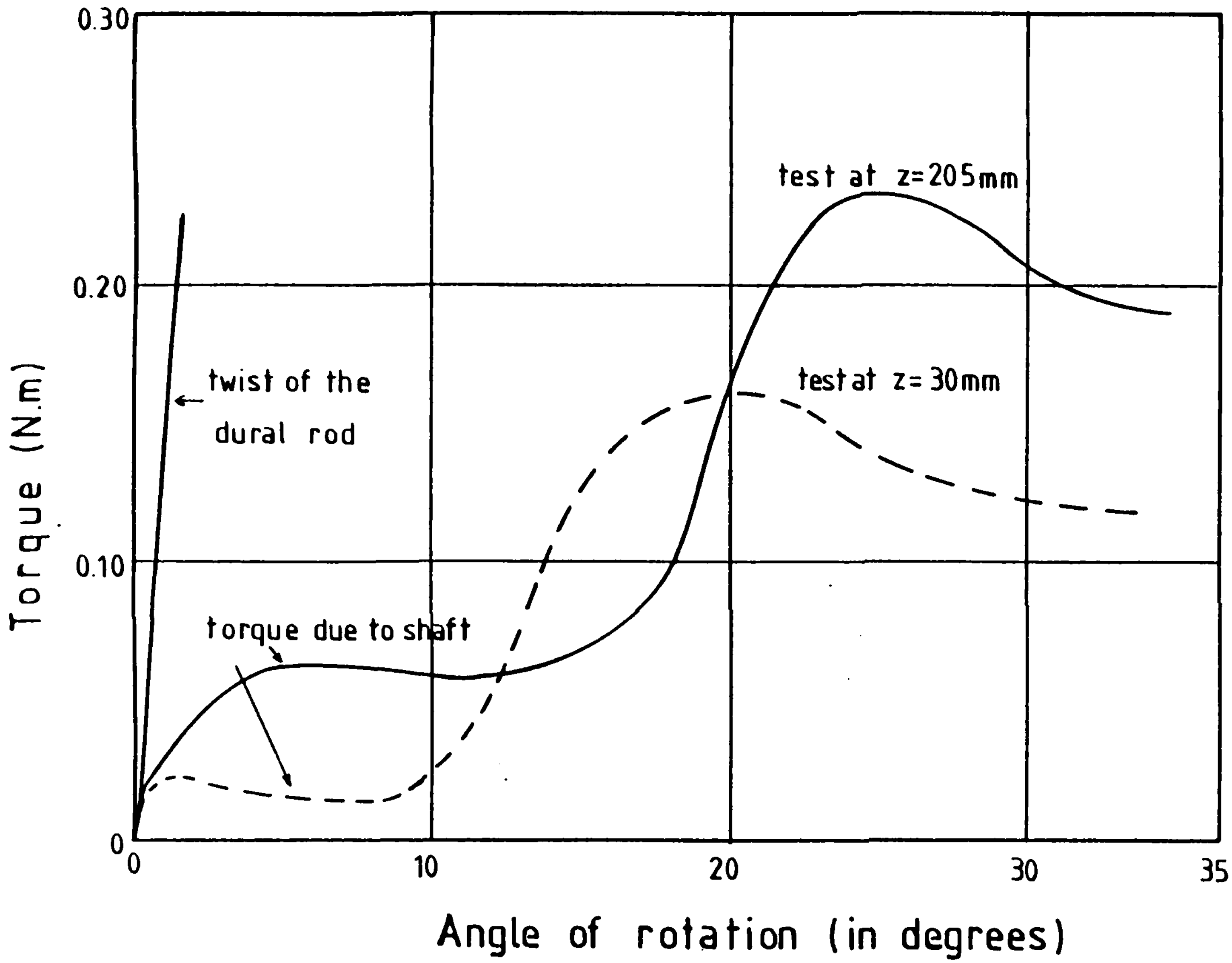



Fig. 4.3: Typical vane records obtaine<sup></sup>d by vane Mark II in clay bed S12B

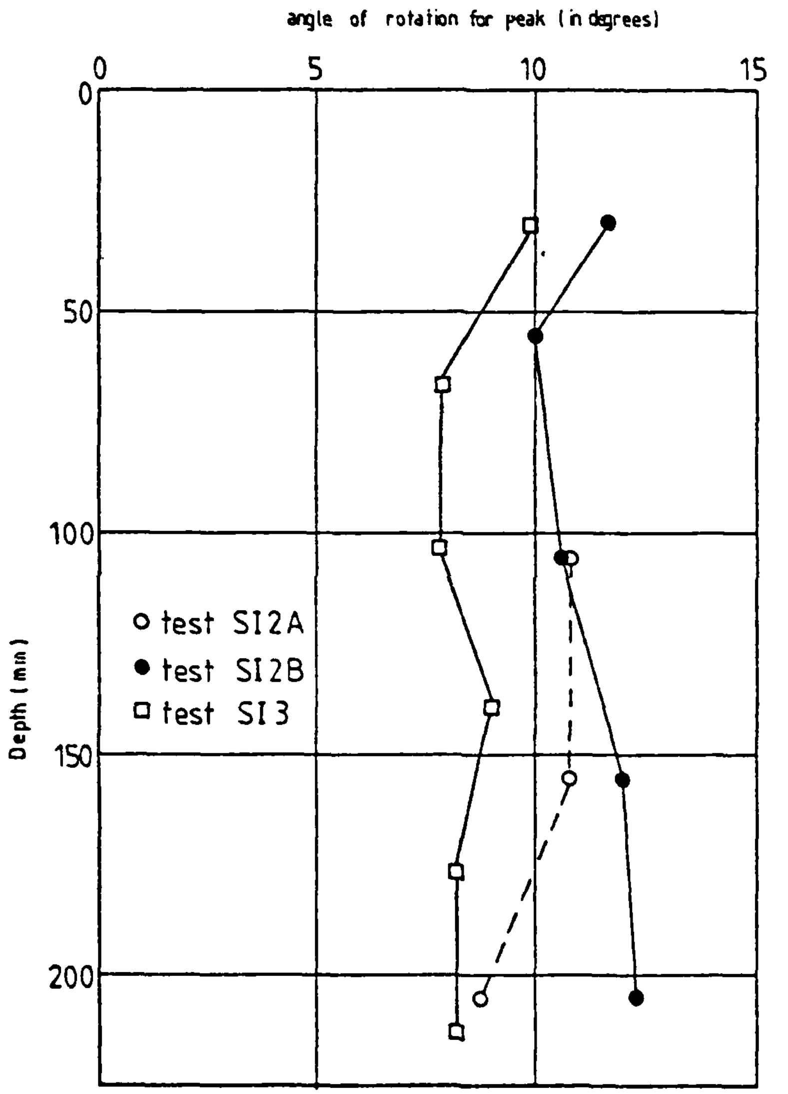



Fig. 4.4: Angle of the rotation for peak measured with vane Mark II

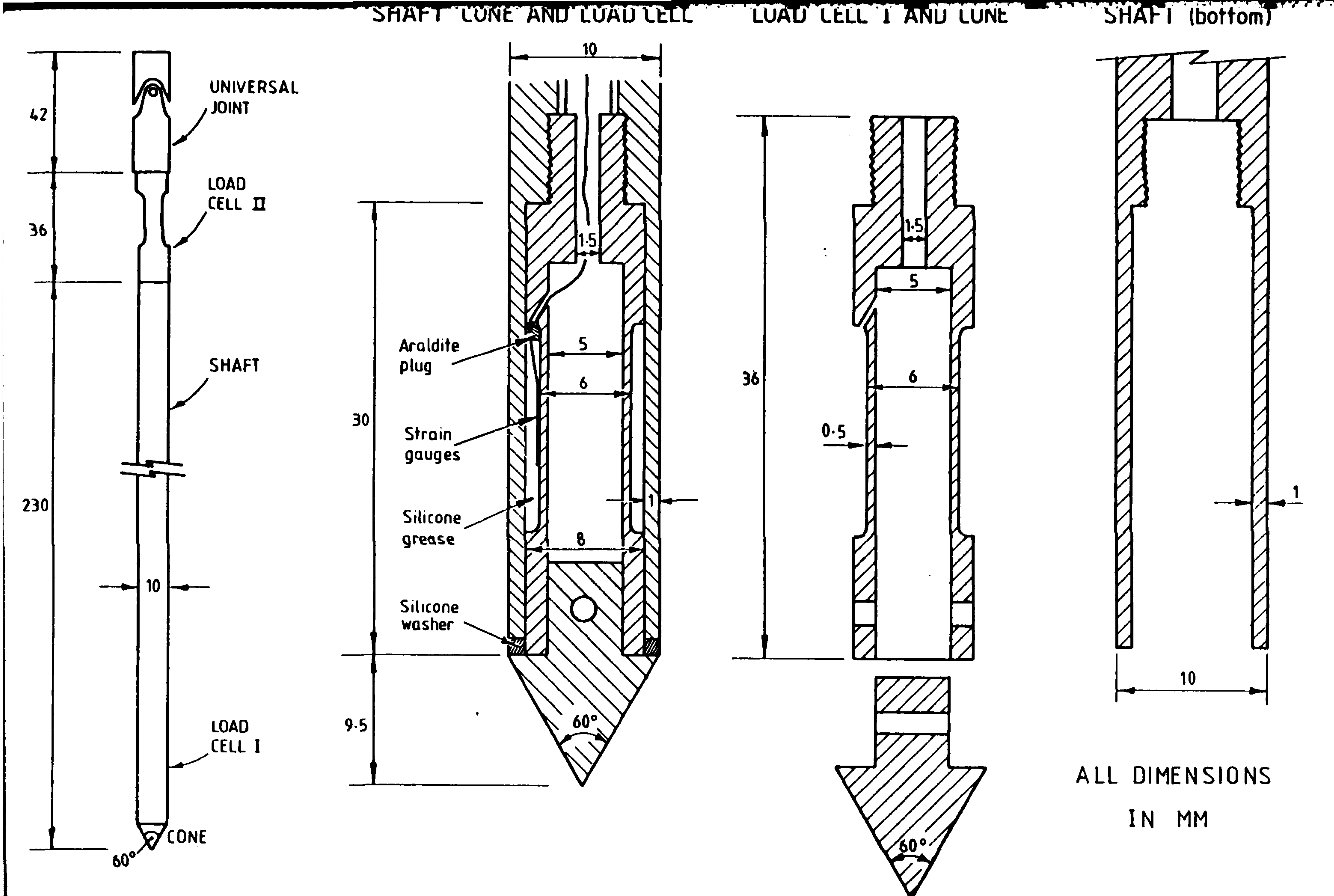



Fig. 4.5: Cone penetrometer Mark II

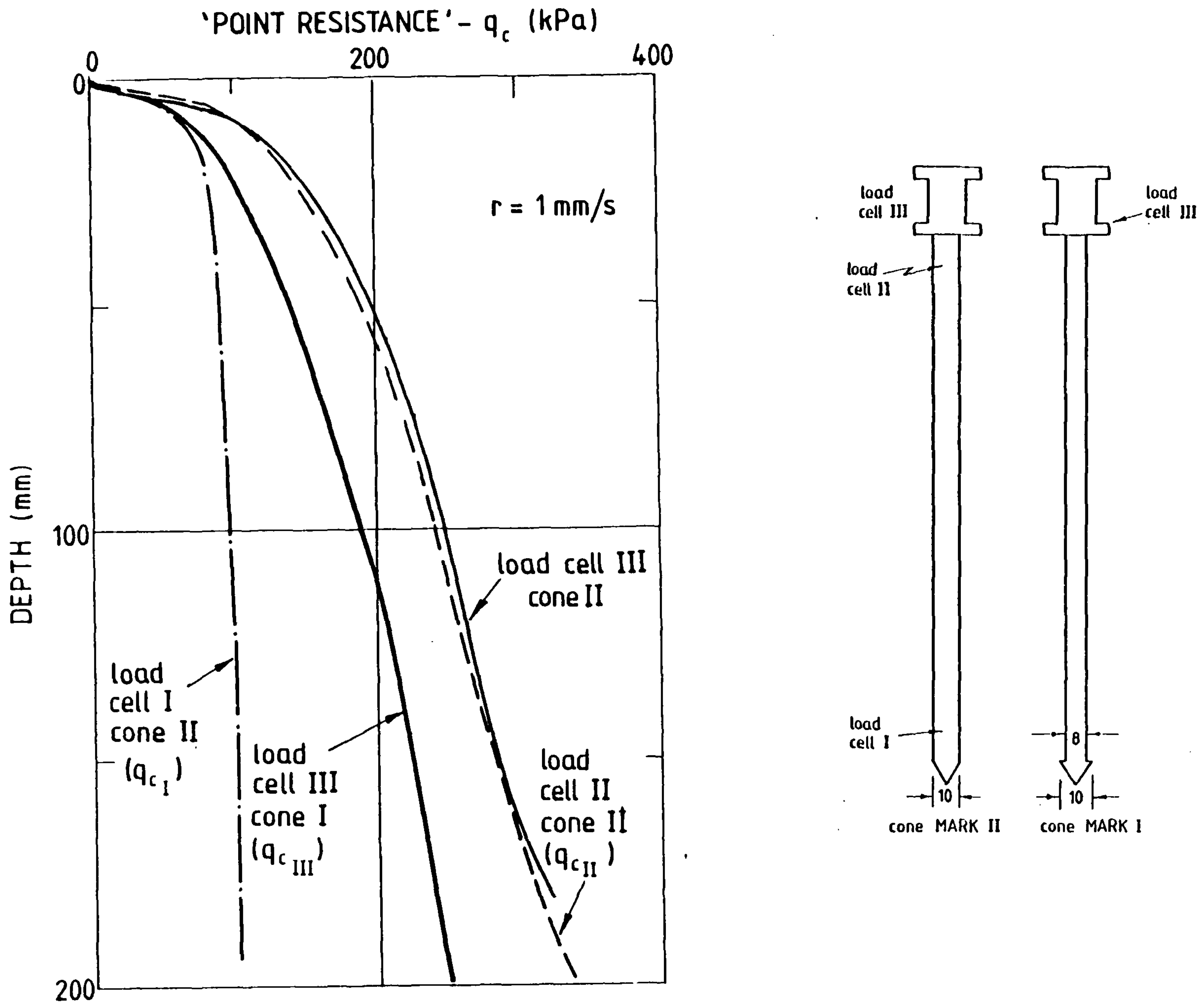



Fig. 4.6: Penetrometer tests with Mark I and Mark II probes

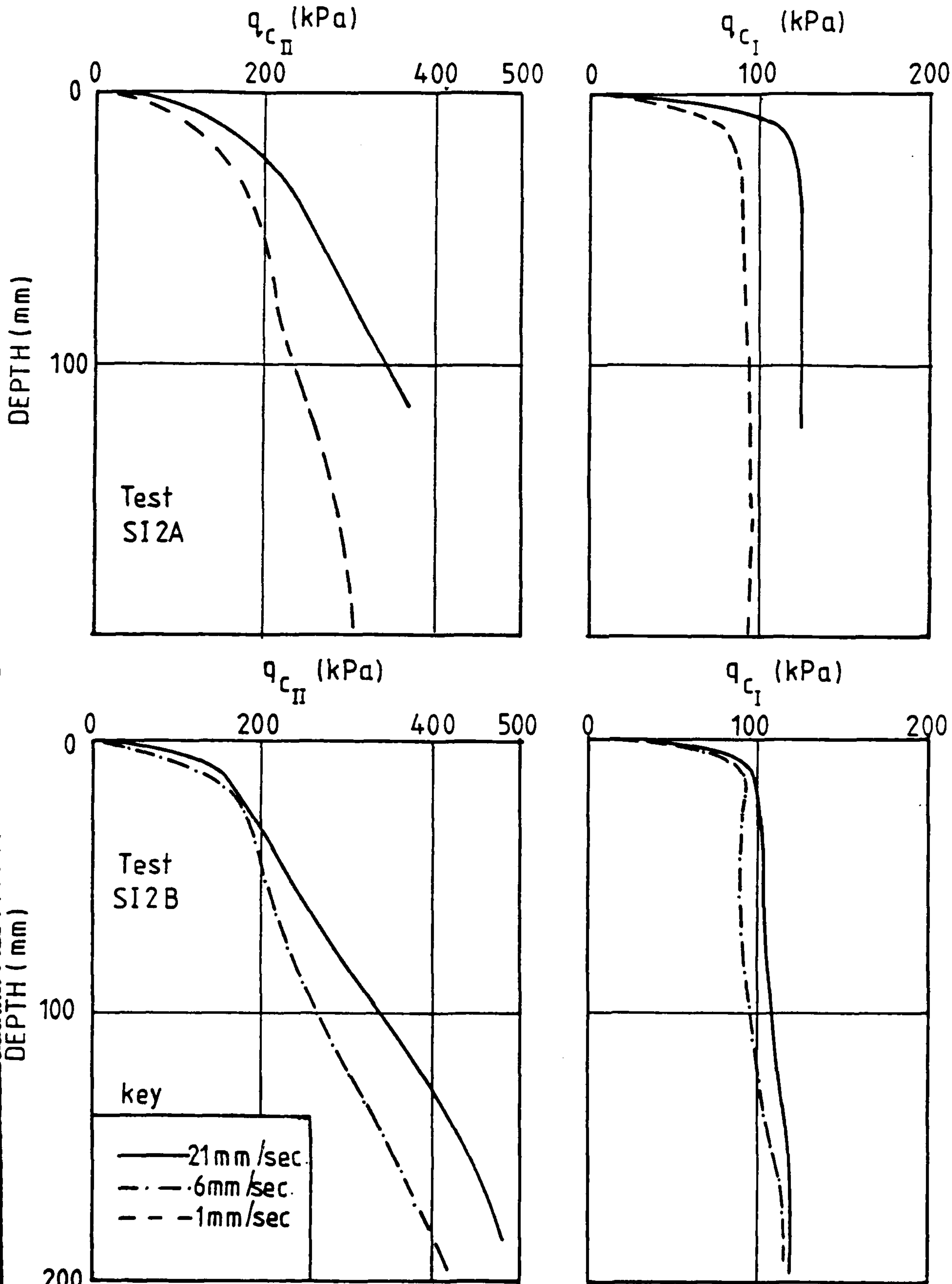



Fig. 4.7: Cone penetrometer tests with Mark II probe

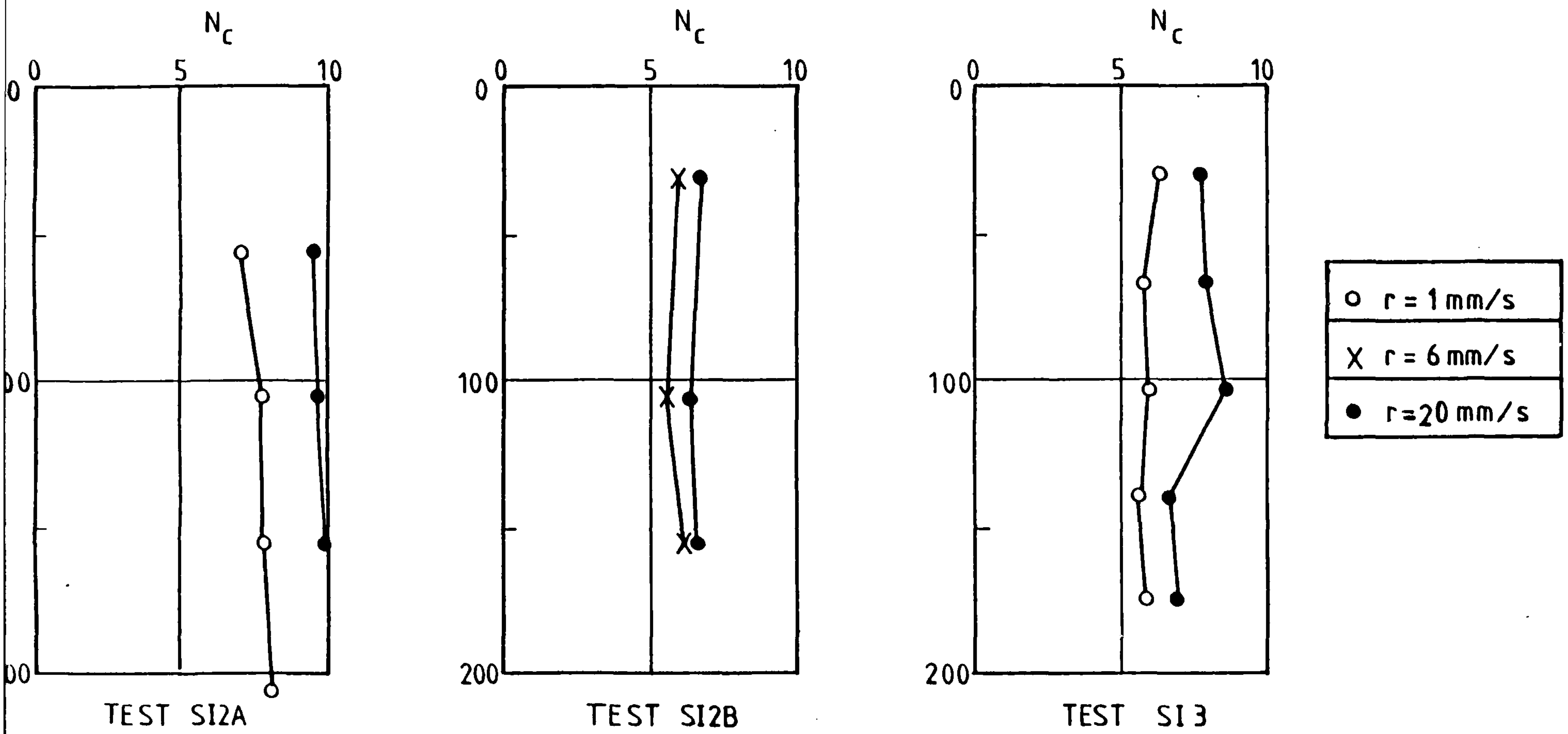



Fig. 4.8: $N_c$ obtained from Mark II vane and Mark II penetrometer

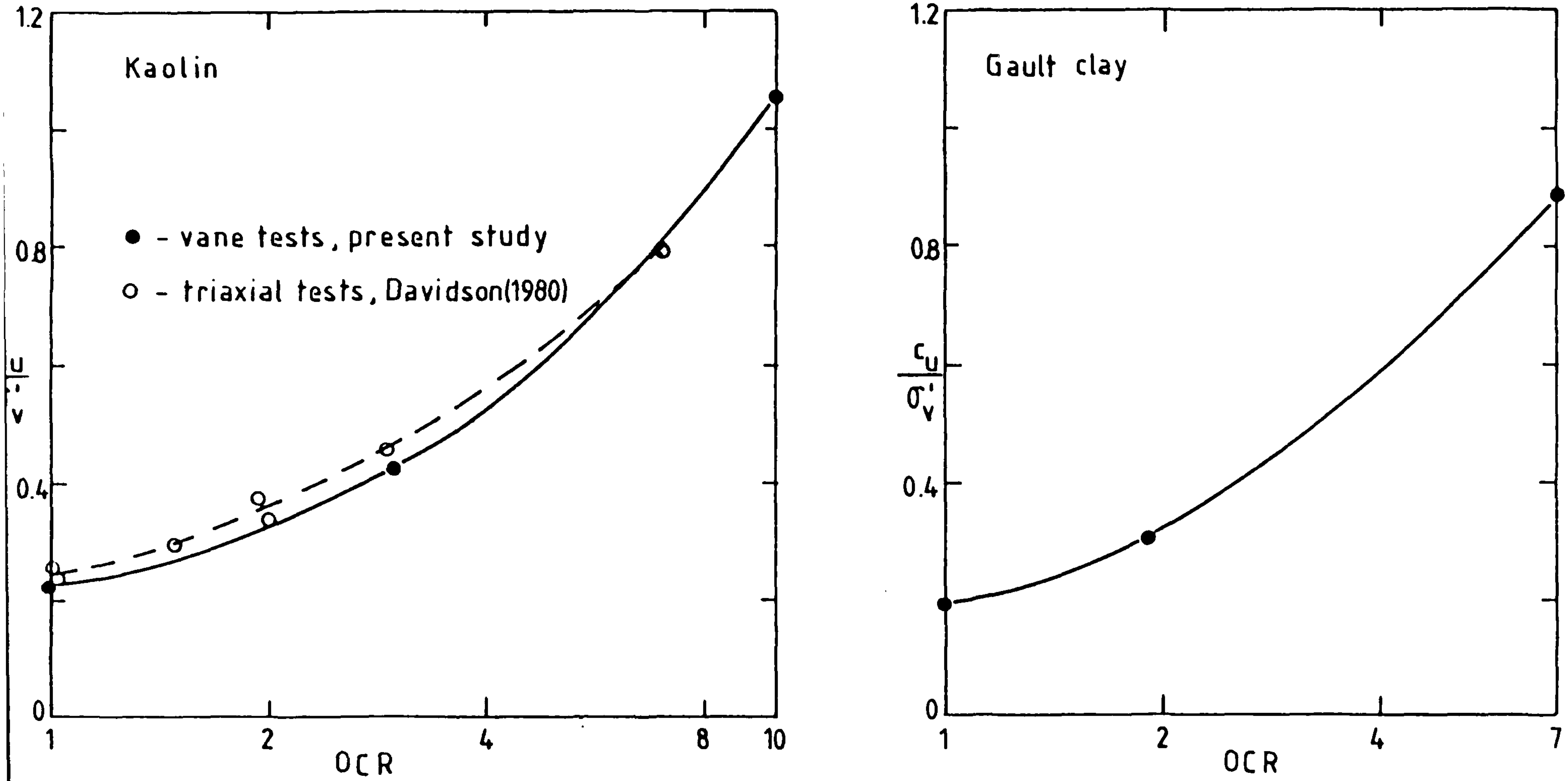



Fig. 5.1: Variation of the normalized undrained strength with OCR for kaolin and Gault clay

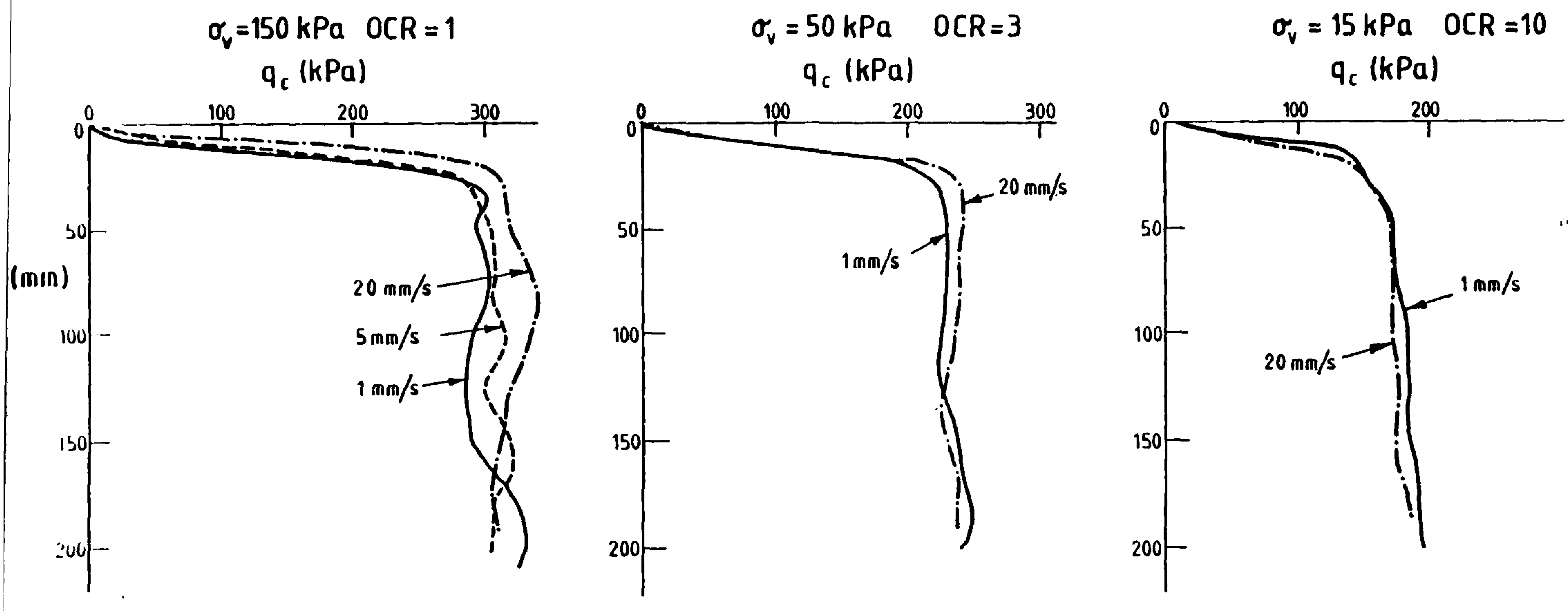



Fig. 5.2: Variation of point resistance with rate of penetration for kaolin

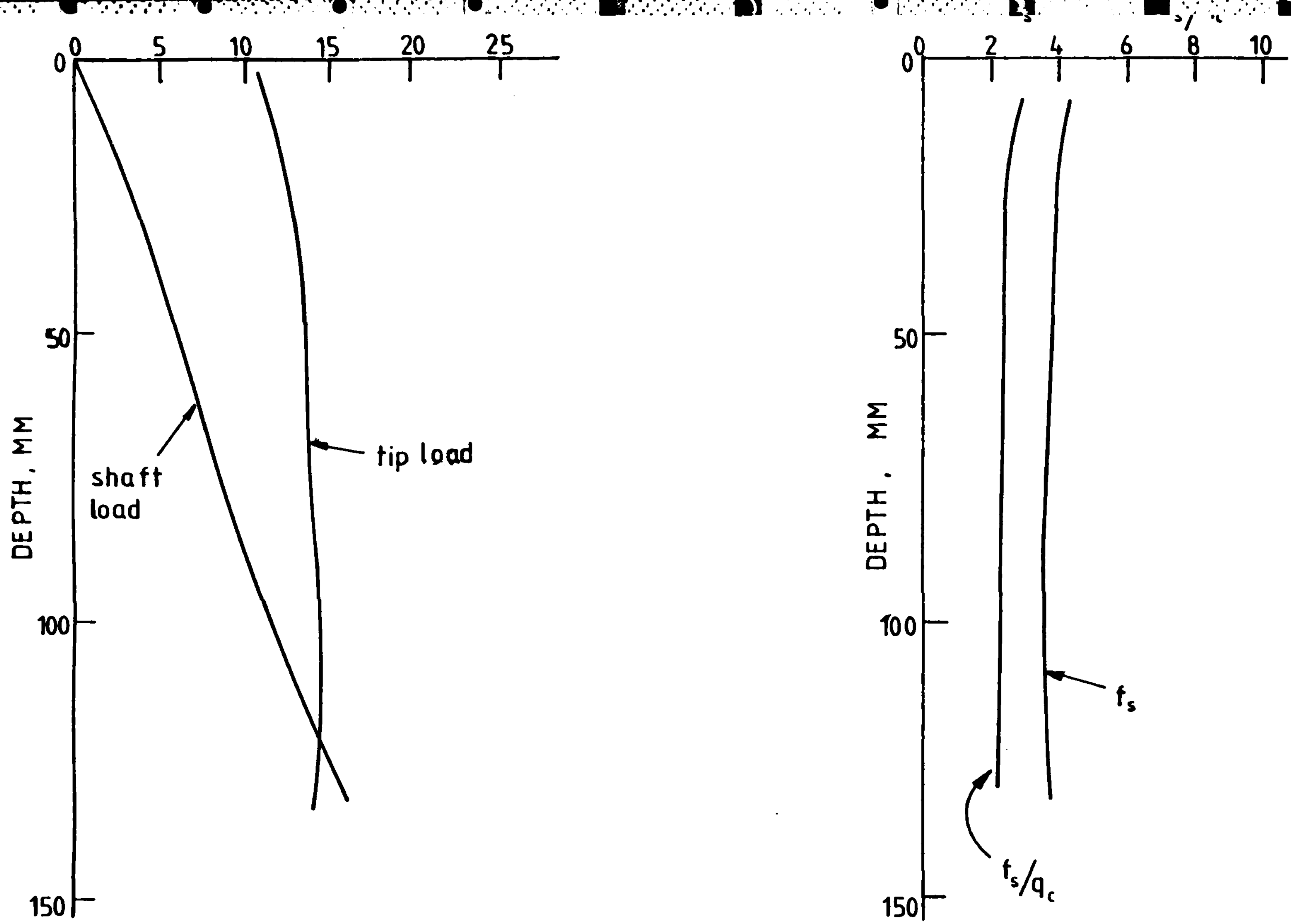



Fig. 5.3: Side friction at a rate of penetration of 1 mm/s, OCR = 10

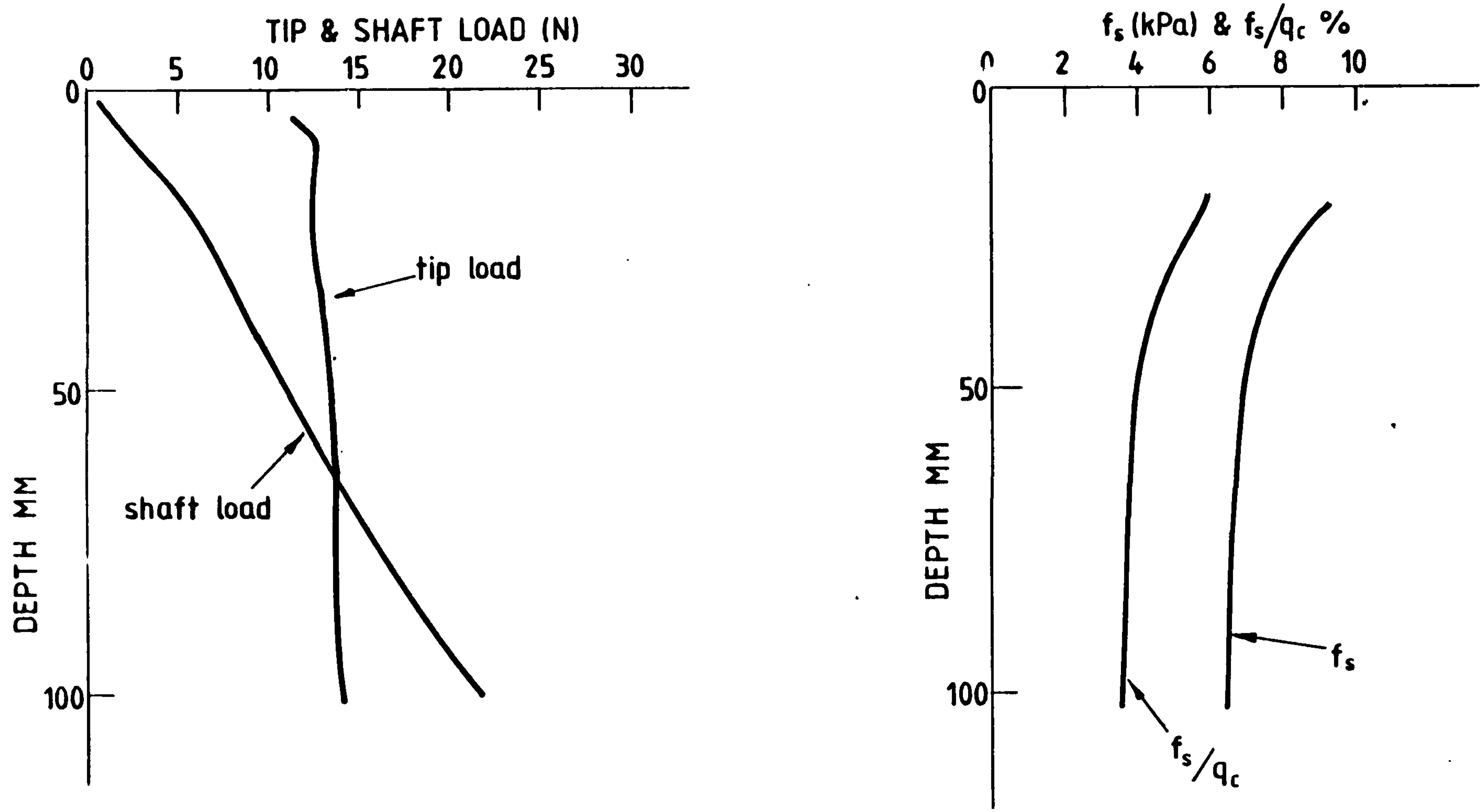
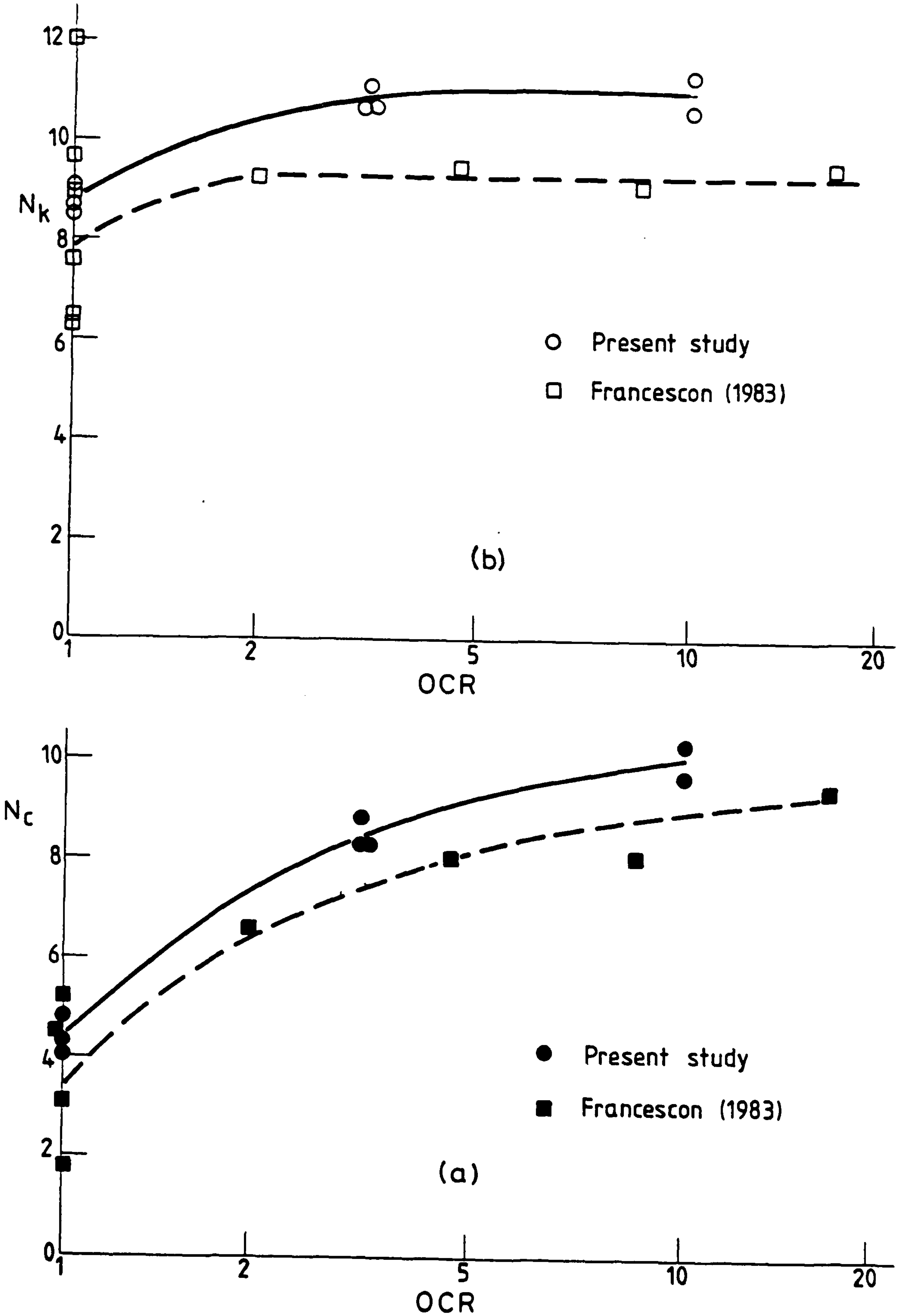



Fig. 5.4: Side friction at a rate of penetration of 20 mm/s, OCR = 10



12
10
8
6
4
2
0
$N_k$
Present study
Francescon (1983)
(b)
1
2
5
10
20
OCR
10
8
6
4
2
0
$N_c$
Present study
Francescon (1983)
(a)
1
2
5
10
20
OCR

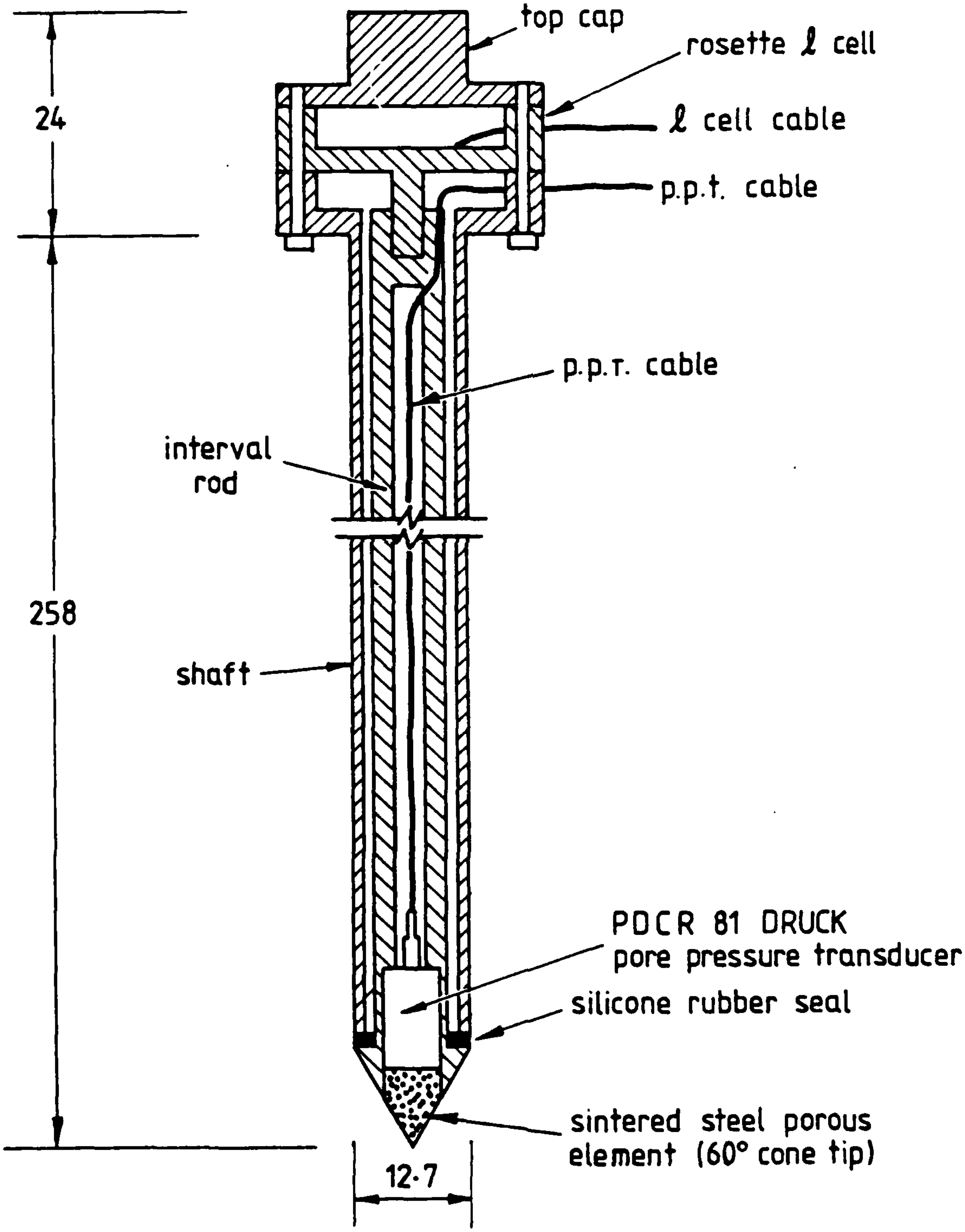



Fig. 5.6: Piezocone

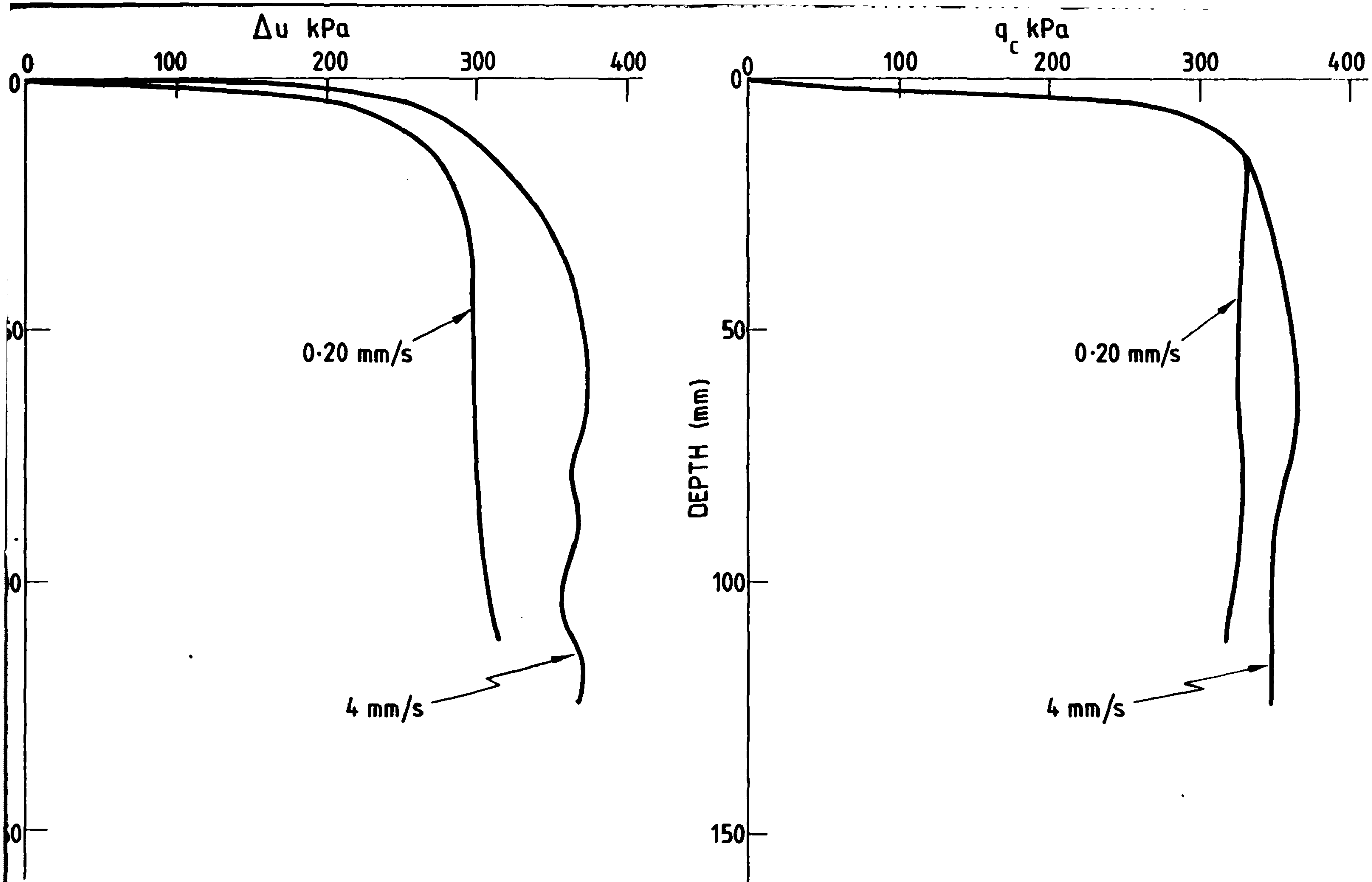



Fig. 5.7: Influence of the rate of penetration in Gault clay, OCR = 1

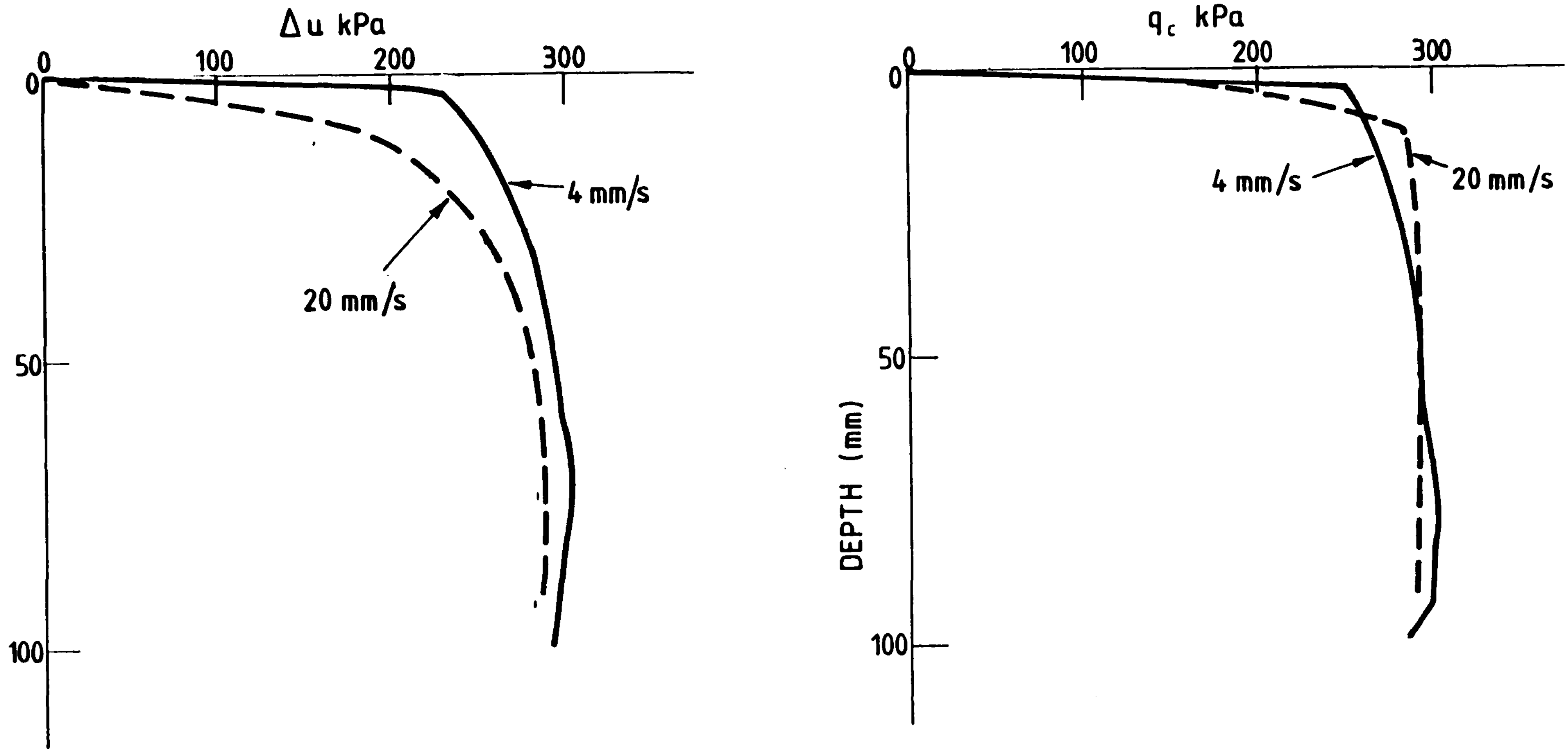



Fig. 5.8: Influence of the rate of penetration in Gault clay, OCR = 3

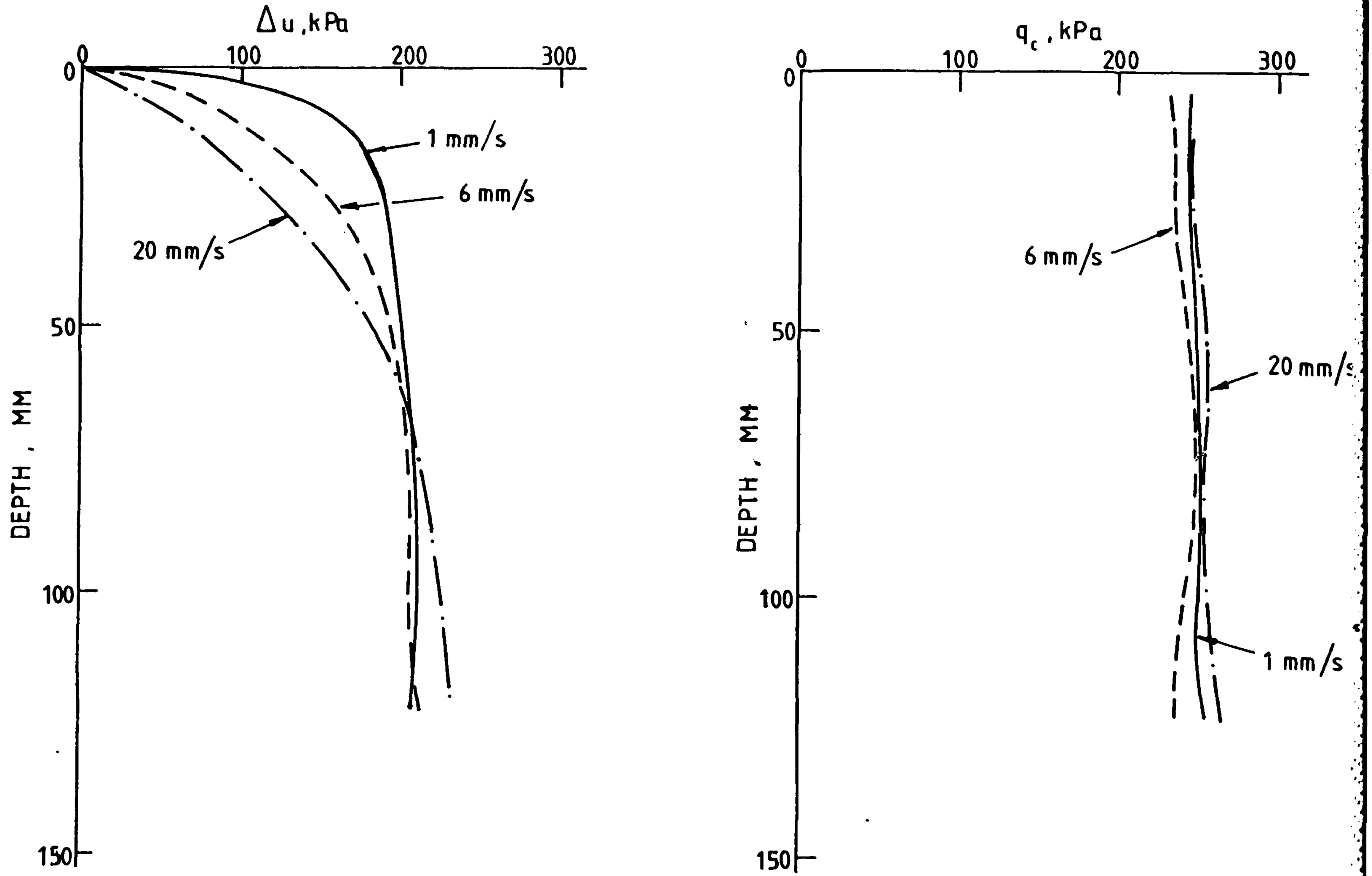



Fig. 5.9: Influence of the rate of penetration in Gault clay, OCR = 10

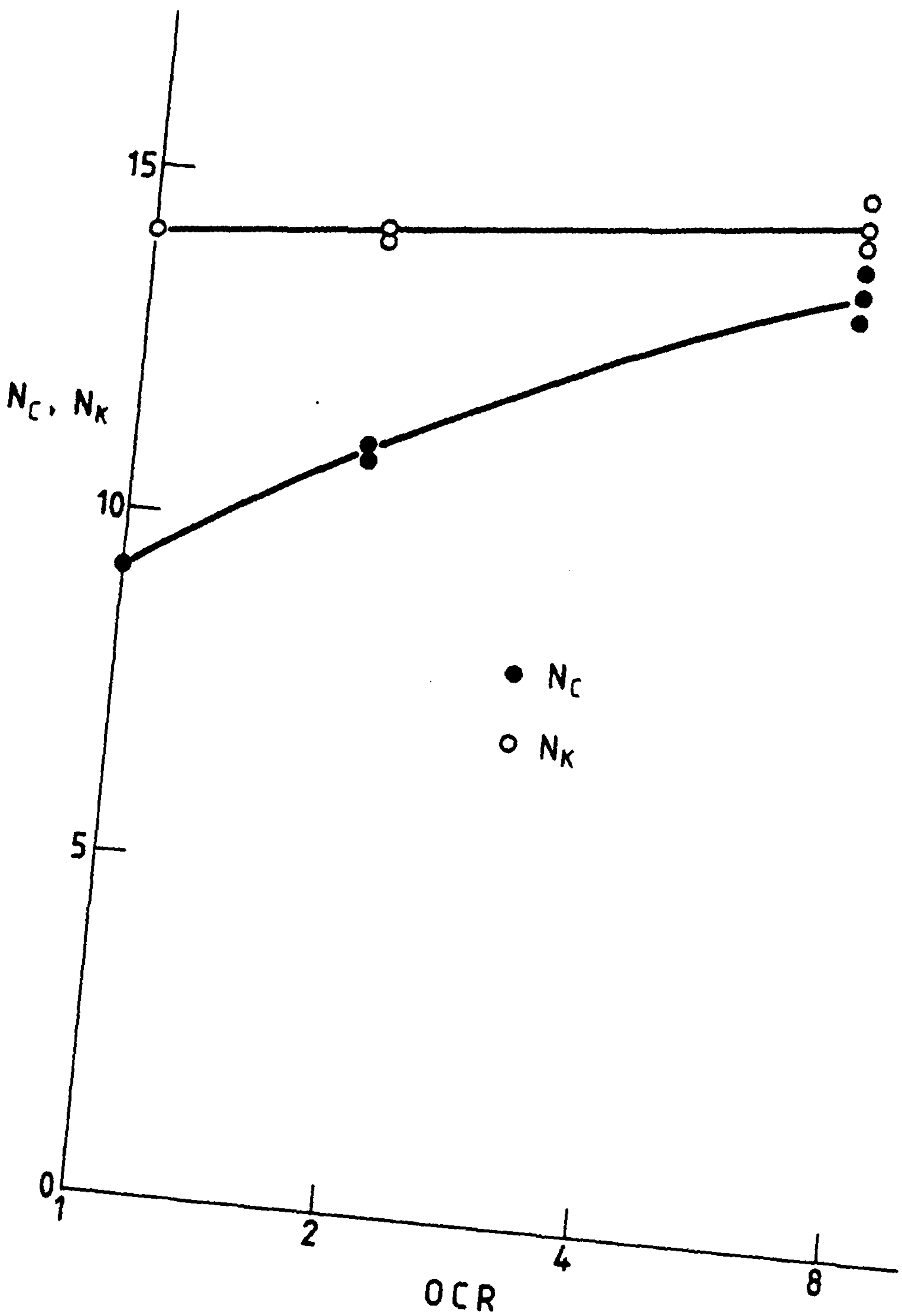



Fig. 5.10: Variation of $N_c$ and $N_k$ with OCR for Gault clay

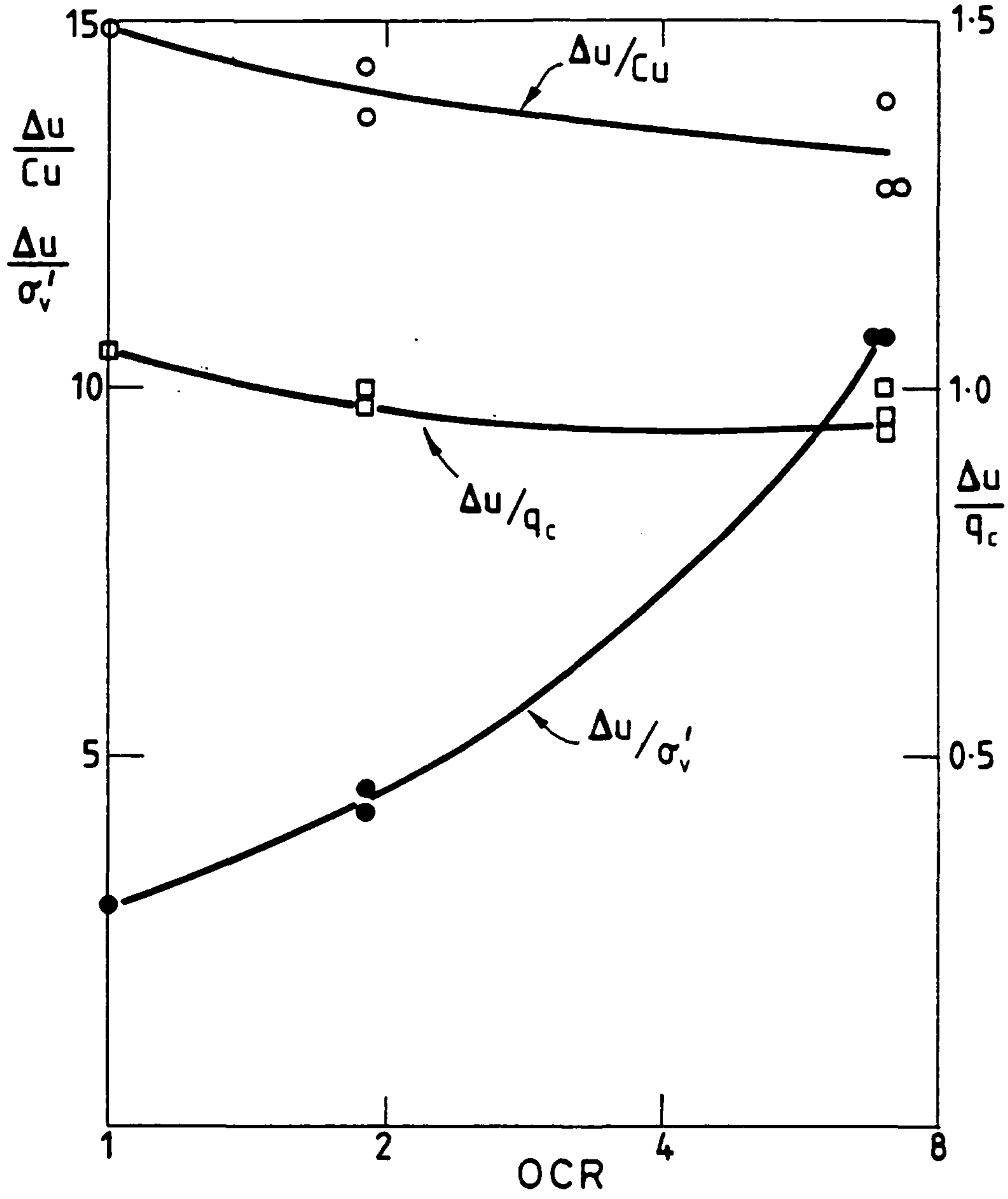
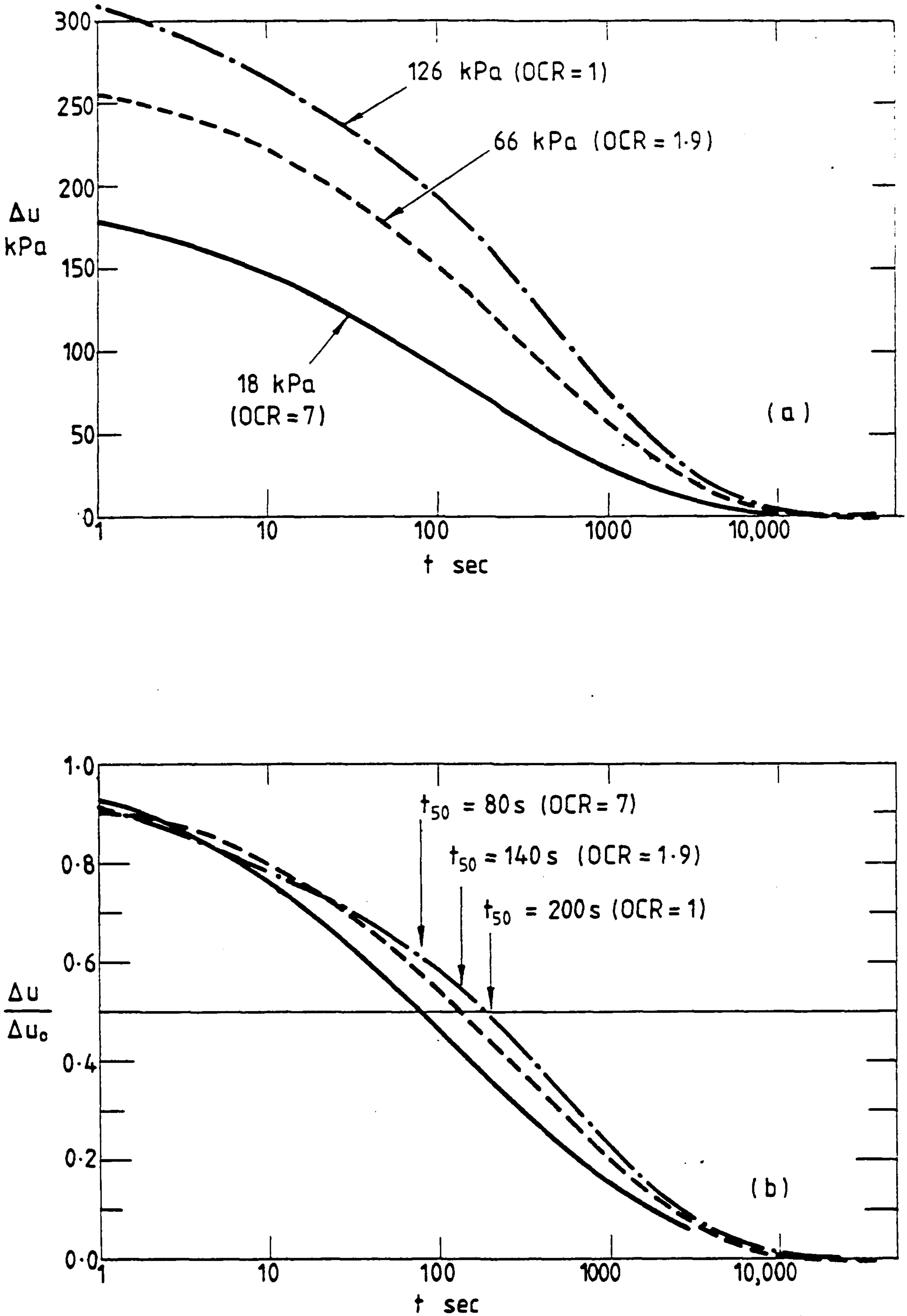



Fig. 5.11: Variation of the normalized pore pressure with OCR for Gault clay


126 kPa (OCR = 1)
66 kPa (OCR = 1·9)
18 kPa
(OCR = 7)
(a)
Δu
kPa
300
250
200
150
100
50
0
1
10
100
1000
10,000
t sec
t50 = 80 s (OCR = 7)
t50 = 140 s (OCR = 1·9)
t50 = 200 s (OCR = 1)
(b)
Δu
Δu0
1·0
0·8
0·6
0·4
0·2
0·0
1
10
100
1000
10,000
t sec

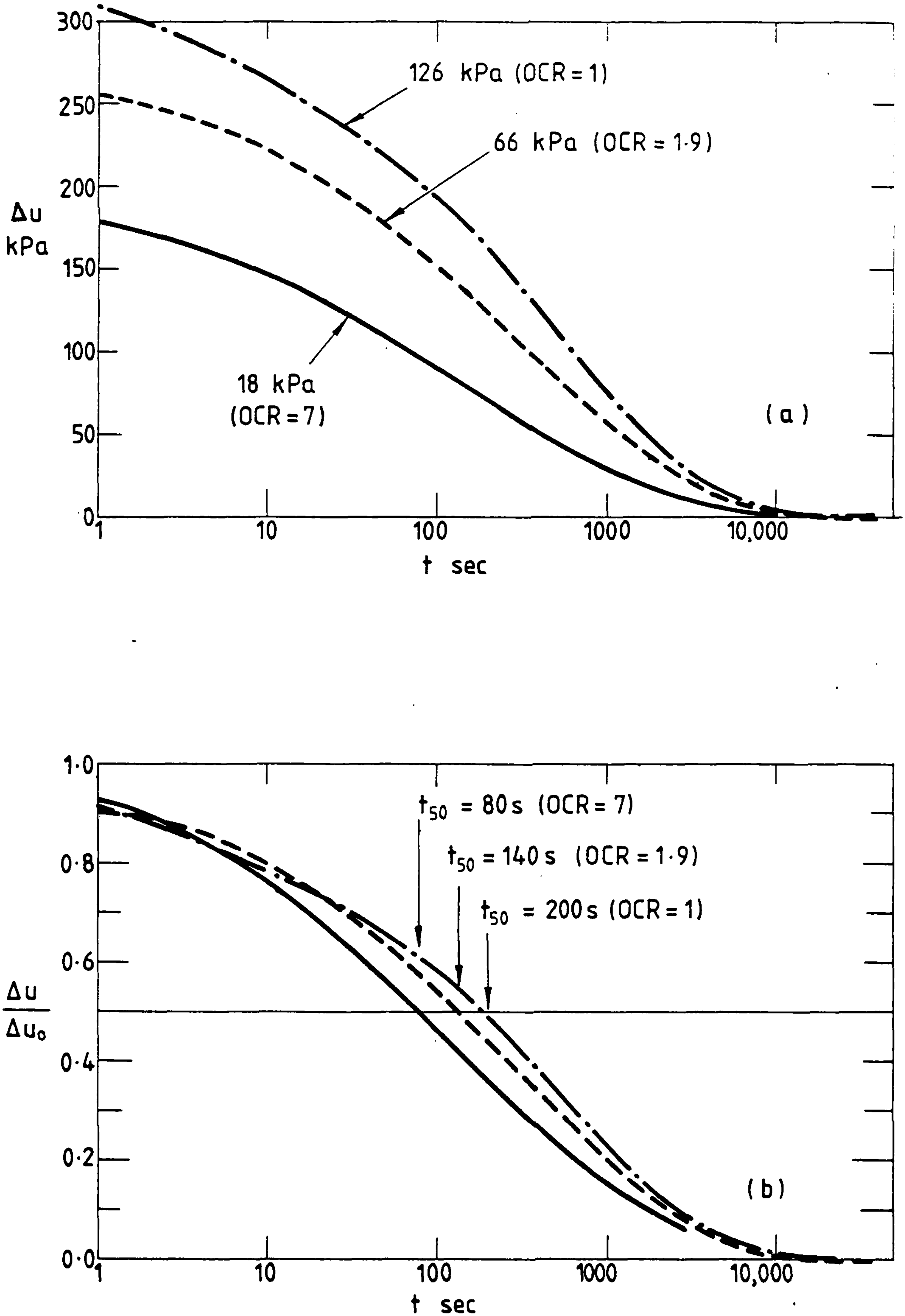



Fig. 5.12: Dissipation tests in

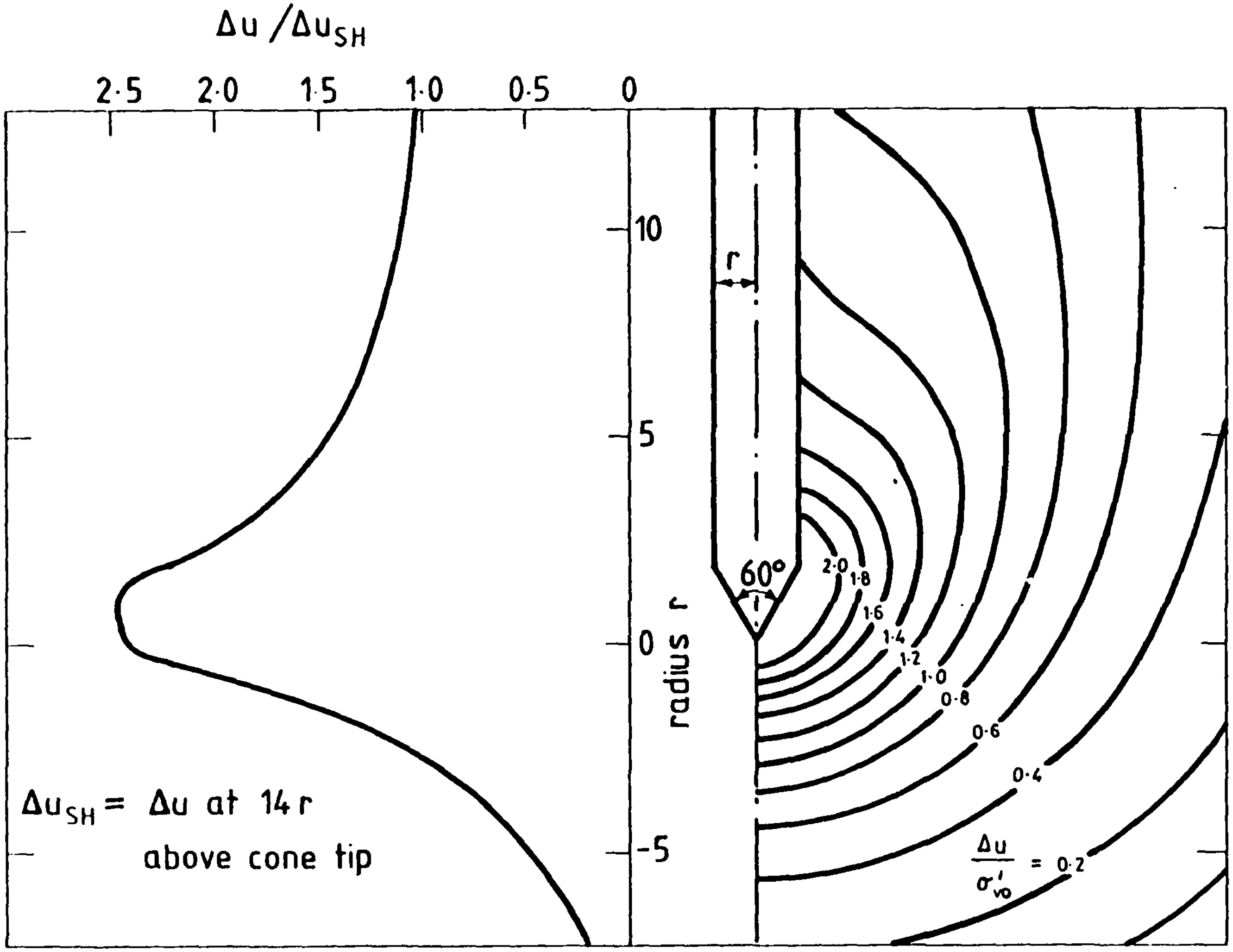



Fig. 5.13: Theoretical distribution of initial normalized pore pressures (after Levadoux and Baligh, 1980)

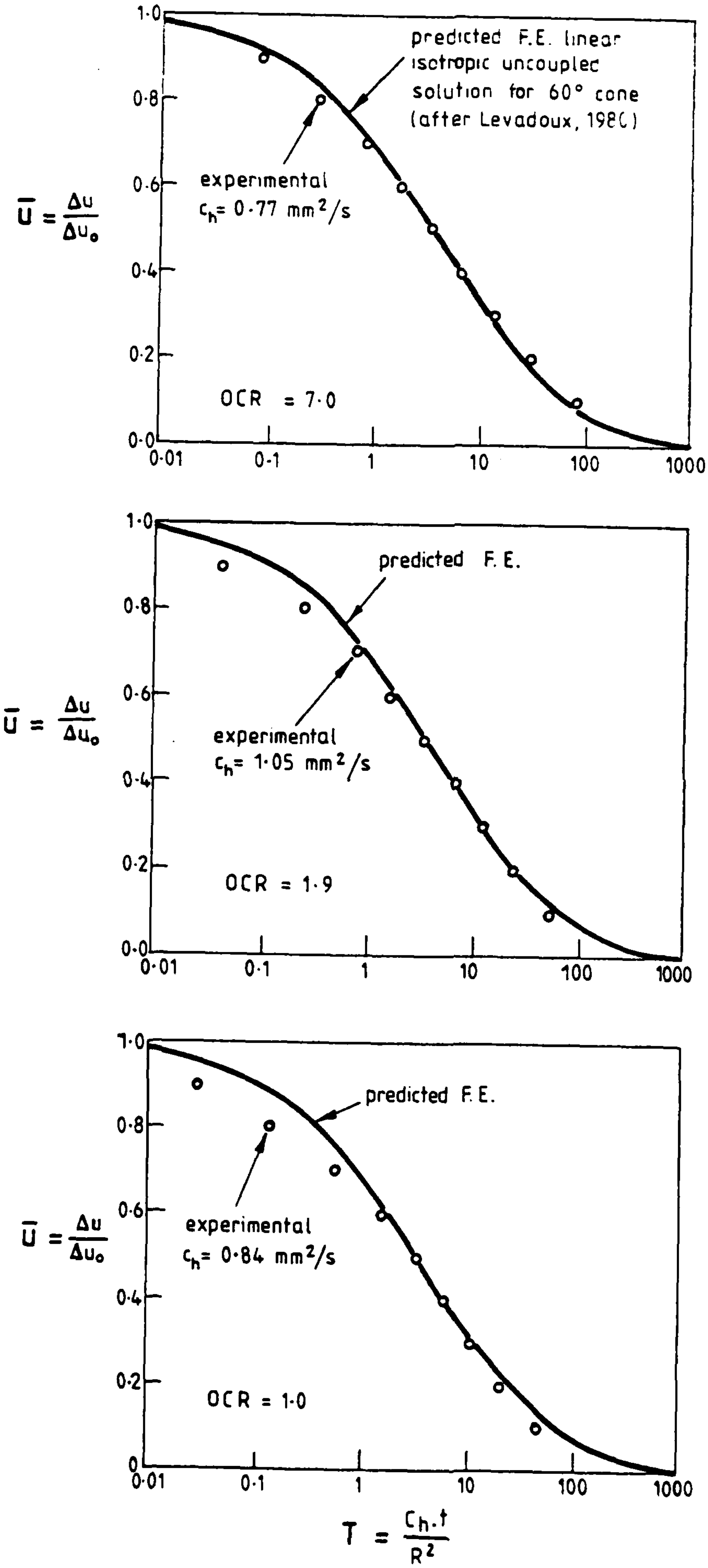



Fig. 5.14: Predicted and measured dissipation curves

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